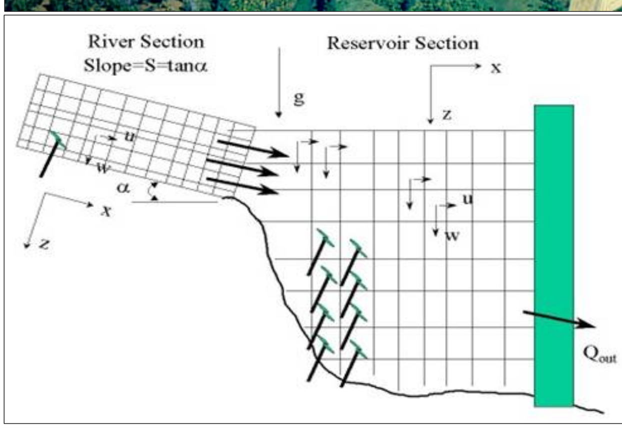
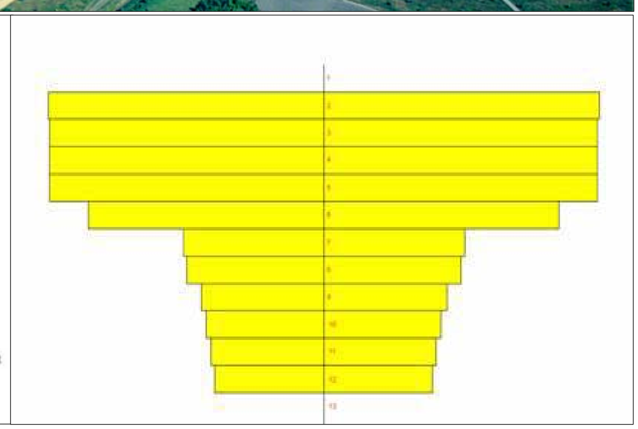
Water Quality Modeling Report

U.S. Army Corps of Engineers
Omaha District

Application of the CE-QUAL-W2 Hydrodynamic and Water Quality Model to Garrison Reservoir, North Dakota





Report Number: CENWO-ED-HA/WQMR/Garrison/2008

November 2008

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **NOV 2008**	2. REPORT TYPE	3. DATES COVERED **00-00-2008 to 00-00-2008**
4. TITLE AND SUBTITLE **Application of the CE-QUAL-W2 Hydrodynamic and Water Quality Model to Garrison Reservoir, North Dakota**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Corps of Engineers,Omaha District,1616 Capital Avenue Ste 9000,Omaha,NE,68102**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a REPORT **unclassified**	b ABSTRACT **unclassified**	c THIS PAGE **unclassified**	**Same as Report (SAR)**	**93**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

(Page left intentionally blank)

Water Quality Modeling Report

Application of the CE-QUAL-W2 Hydrodynamic and Water Quality Model to Garrison Reservoir, North Dakota

(Report Number: CENWO-ED-HA/WQMR/Garrison/2008)

Prepared by:

Hydrology Section
Water Control and Water Quality Section
Hydrologic Engineering Branch
Engineering Division
Omaha District
U.S. Army Corps of Engineers

November 2008

This document is approved for release:

For Information Regarding This Document Please Contact:

U.S. Army Corps of Engineers, Omaha District
1616 Capitol Avenue
Omaha, Nebraska 68102-4901
(402) 995-2314

TABLE OF CONTENTS

List of Tables

List of Figures

EXECUTIVE SUMMARY

A priority water quality management need identified by the Omaha District is the capability to quantifiably assess, with acceptable uncertainty, the affects that operation and regulation of the six Missouri River Mainstem System (Mainstem System) projects have on water quality of the Missouri River and the impounded reservoirs. To meet this need, the Omaha District is applying the CE-QUAL-W2 Hydrodynamic and Water Quality Model to the six Missouri River mainstem reservoirs. The goal is to have linked, fully-functioning CE-QUAL-W2 models in place for all the Mainstem System projects that meets the uncertainty requirements of appropriate decision-makers. This report documents the application of the CE-QUAL-W2 model to Garrison Reservoir in North Dakota.

Garrison Dam which impounds Lake Sakakawea operates with a bottom withdrawal which draws cold discharge water from the lake bottom. Repeated years of drought in the Upper Missouri River Basin and the bottom withdrawal have been detrimental to water temperature and dissolved oxygen in the reservoir, negatively impacting the coldwater habitat (CWH) volume as defined by the state of North Dakota.

The District developed a CE-QUAL-W2 water quality model for Garrison Reservoir after the completion of the three-year intensive water quality survey to assess CWH volume in the reservoir and to evaluate the effectiveness of several implemented water quality measures including plywood intake barriers, head gate closure, modification of the daily flow cycle and a hypothetical high-level reservoir withdrawal. The reservoir model was configured to compute temperature, dissolved oxygen, and organic nutrients using semi-deterministic algorithms, and it was calibrated to 2003 through 2007 water temperature and dissolved oxygen measurements.

The analysis revealed that the plywood barriers had a limited impact on overall temperature and dissolved oxygen concentrations within the reservoir bottom. The barriers slightly increased CWH volume (T < 15 degrees Celsius, dissolved oxygen concentration > 5 mg/L) by preserving colder water in the reservoir bottom. CWH savings as a result of the plywood barrier implementation in the reservoir simulations ranged from 0.0 to 0.46 million acre-feet (MAF). Simulated flow peaking produced relatively no change in average reservoir discharge temperatures and no CWH savings. The CE-QUAL-W2 model was unable to recreate the headgate closure water quality measure due to model limitations.

Simulations of the hypothetical high-level reservoir withdrawal revealed that a withdrawal elevation 35 meters (115 feet) above the normal bottom withdrawal elevation could increase withdrawal temperatures and downstream water temperatures during summer stratification by 3.0 to 5.0 degrees C. CWH savings ranged from 0.40 to 1.48 MAF.

(Page left intentionally blank)

1 INTRODUCTION

1.1 APPLICATION OF THE CE-QUAL-W2 HYDRODYNAMIC AND WATER QUALITY MODEL TO THE MISSOURI RIVER MAINSTEM SYSTEM RESERVOIRS

1.1.1 WATER QUALITY MODELING NEED

A priority water quality management need identified by the Omaha District (District) is the capability to quantifiably assess, with acceptable uncertainty, the affects that operation and regulation of the six Missouri River Mainstem System (Mainstem System) projects have on water quality of the Missouri River and the impounded reservoirs (USACE, 2008). To meet this need, the District developed a plan to apply the CE-QUAL-W2 Hydrodynamic and Water Quality Model to the six Mainstem System reservoirs: Fort Peck (Montana), Garrison (North Dakota), Oahe (North and South Dakota), Big Bend (South Dakota), Fort Randall (South Dakota), and Gavins Point (South Dakota and Nebraska). The District is approaching application of the CE-QUAL-W2 model to the Mainstem System reservoirs as an ongoing, iterative process. Water quality data is collected at the reservoirs and the model is applied and calibrated. The goal is to have linked, fully-functioning water quality models in place for all the Mainstem System reservoirs that meets the uncertainty requirements of appropriate decision-makers.

CE-QUAL-W2 is a "state-of-the-art" model that can greatly facilitate addressing water quality management issues at the Mainstem System projects. CE-QUAL-W2 mechanistically models basic physical, chemical, and biological processes such as temperature, nutrient, algae, dissolved oxygen, organic matter, and sediment relationships. Once applied and calibrated, the model can reliably predict reservoir water quality conditions based on changes in environmental conditions or project operations and regulation. The ability to reliably predict reservoir water quality conditions under different environmental, operational, and regulation situations will allow the District to determine if water quality at specific projects may be impacted by project operations and regulation. As such, the model will allow the District to proactively assess how proposed project operations and regulation may affect water quality, and allow appropriate water quality management measures to be identified and implemented.

1.1.2 PRIOR APPLICATION OF THE CE-QUAL-W2 MODEL TO THE MAINSTEM SYSTEM RESERVOIRS

An early version of the CE-QUAL-W2 model was applied to four of the Mainstem System reservoirs in the early 1990's (i.e., Ft. Peck, Garrison, Oahe, and Fort Randall). The application of the model was part of the supporting technical documentation of the Environmental Impact Statement (EIS) that was prepared for the Missouri River Master Water Control Manual Review and Update Study. The results of the model application were included as an Appendix to the Review and Update Study – "Volume 7B: Environmental Studies, Reservoir Fisheries, Appendix C – Coldwater Habitat Model, Temperature and Dissolved Oxygen Simulations for the Upper Missouri River Reservoirs" (Cole et. al., 1994). The report (Cole et. al, 1994) provided results of applying the model to the four reservoirs regarding the effects of operational changes on coldwater fish habitat in the reservoir. This early application of the model represents the best results that could be obtained based on the model version and water quality data available at that time, and provided predictive capability for two system operational variables of concern; end-of-month stages and monthly average releases.

Although application of the early CE-QUAL-W2 model met its intended purpose at the time, a lack of available water quality data placed limitations on its full utilization. These limitations were discussed in the Master Water Control Review and Update Study report (Cole et. al, 1994). The following excerpt is taken from that report:

"Steps should be taken to obtain a suitable database that can be used to calibrate the entire suite of water quality algorithms in the model. It is almost a certainty that water quality issues will remain important in the future."

The current version of the CE-QUAL-W2 model has incorporated numerous enhancements over the earlier version that was applied to the four Mainstem System reservoirs in the early 1990's. These enhancements, among other things, include improvements to the numerical solution scheme, water quality algorithms, two-dimensional modeling of the water basin, code efficiencies, and user-model interface. Communication with the author of the earlier version of the CE-QUAL-W2 model applied to the Mainstem System reservoirs and current model support personnel indicated that the District should pursue implementing the current version of the model (personal communication, Thomas M. Cole, USACE/ERDC).

1.1.3 CURRENT APPLICATION OF THE CE-QUAL-W2 MODEL TO THE MAINSTEM SYSTEM RESERVOIRS

The plan for applying the current CE-QUAL-W2 model to a single Mainstem System reservoir encompasses a 5-year period. During years 1 through 3 an intensive water quality survey is conducted on the reservoir to collect the water quality data needed to fully apply the model. Application and calibration of the model occurs in years 4 and 5. Resource limitations required that the initiation of intensive water quality surveys at the Mainstem System reservoirs be staggered annually. The order and year of initiation of the intensive water quality surveys at the Mainstem System reservoirs are: 1) Garrison (2003), 2) Fort Peck (2004), 3) Oahe (2005), 4) Fort Randall (2006), 5) Big Bend (2008), and Gavins Point (2008). Once calibrated for a project, the model will be used to develop a water quality management report and objectives for each of the Mainstem System projects.

This report documents the application of the CE-QUAL-W2 model to Garrison Reservoir in North Dakota.

1.2 REGULATION OF THE MAINSTEM SYSTEM

The Mainstem System is a hydraulically and electrically integrated system that is regulated to obtain the optimum fulfillment of the multipurpose benefits for which the dams and reservoirs were authorized and constructed. The Congressionally authorized purposes of the Mainstem System are flood control, navigation, hydropower, water supply, water quality, irrigation, recreation, and fish and wildlife (including threatened and endangered species). The Mainstem System is operated under the guidelines described in the Missouri River Mainstem System Master Water Control Manual, (Master Manual) (USACE-RCC, 2004). The Master Manual details reservoir regulation for all authorized purposes as well as emergency regulation procedures in accordance with the authorized purposes.

Mainstem System regulation is, in many ways, a repetitive annual cycle that begins in late winter with the onset of snowmelt. The annual melting of mountain and plains snow packs along with spring and summer rainfall produces the annual runoff into the Mainstem System. In a typical year, mountain snow pack, plains snow pack, and rainfall events respectively contribute 50, 25, and 25 percent of the annual runoff to the Mainstem System. After reaching a peak, usually during July, the amount of water stored in the Mainstem System declines until late in the winter when the cycle begins anew. A similar pattern may be found in rates of releases from the Mainstem System, with the higher levels of flow from mid-March to late November, followed by low rates of winter discharge from late November until mid-March, after which the cycle repeats.

To maximize the service to all the authorized purposes, given the physical and authorization limitations of the Mainstem System, the total storage available in the Mainstem System is divided into four regulation zones that are applied to the individual reservoirs. These four regulation zones are: 1) Exclusive Flood Control Zone, 2) Annual Flood Control and Multiple Use Zone, 3) Carryover Multiple Use Zone, and 4) Permanent Pool Zone.

1.2.1 EXCLUSIVE FLOOD CONTROL ZONE

Flood control is the only authorized purpose that requires empty space in the reservoirs to achieve the objective. A top zone in each Mainstem System reservoir is reserved for use to meet the flood control requirements. This storage space is used only for detention of extreme or unpredictable flood flows and is evacuated as rapidly as downstream conditions permit, while still serving the overall flood control objective of protecting life and property. The Exclusive Flood Control Zone encompasses 4.7 MAF and represents the upper 6 percent of the total Mainstem System storage volume. This zone, from 73.3 MAF down to 68.7 MAF, is normally empty. The four largest reservoirs, Fort Peck, Garrison, Oahe, and Fort Randall, contain 97 percent of the total storage reserved for the Exclusive Flood Control Zone.

1.2.2 ANNUAL FLOOD CONTROL AND MULTIPLE USE ZONE

An upper “normal operating zone” is reserved annually for the capture and retention of runoff (normal and flood) and for annual multiple-purpose regulation of this impounded water. The Mainstem System storage capacity in this zone is 11.7 MAF and represents 16 percent of the total Mainstem System storage. This storage zone, which extends from 68.7 MAF down to 57.0 MAF, will normally be evacuated to the base of this zone by March 1 to provide adequate storage capacity for capturing runoff during the next flood season. On an annual basis, water will be impounded in this zone, as required to achieve the Mainstem System flood control purpose, and also be stored in the interest of general water conservation to serve all the other authorized purposes. The evacuation of water from the Annual Flood Control and Multiple Use Zone is scheduled to maximize service to the authorized purposes that depend on water from the Mainstem System. Scheduling releases from this zone is limited by the flood control objective in that the evacuation must be completed by the beginning of the next flood season. This is normally accomplished as long as the evacuation is possible without contributing to serious downstream flooding. Evacuation is, therefore, accomplished mainly during the summer and fall because Missouri River ice formation and the potential for flooding from higher release rates limit release rates during the December through March period.

1.2.3 CARRYOVER MULTIPLE USE ZONE

The Carryover Multiple Use Zone is the largest storage zone extending from 57.0 MAF down to 18.0 MAF and represents 53 percent of the total Mainstem System storage volume. Serving the authorized purposes during an extended drought is an important regulation objective of the Mainstem System. The Carryover Multiple Use Zone provides a storage reserve to support authorized purposes during drought conditions. Providing this storage is the primary reason the upper three reservoirs of the Mainstem System are so large compared to other Federal water resource projects. The Carryover Multiple Use Zone is often referred to as the “bank account” for water in the Mainstem System because of its role in supporting authorized purposes during critical dry periods when the storage in the Annual Flood Control and Multiple Use Zone is exhausted. Only the reservoirs at Fort Peck, Garrison, Oahe, and Fort Randall have this storage as a designated storage zone. The three larger reservoirs (Fort Peck, Garrison, and Oahe) provide water to the Mainstem System during drought periods to provide for authorized purposes. During drought periods, the three smaller projects (i.e., Fort Randall, Big Bend, and Gavins Point) reservoir levels are maintained at the same elevation they would be at if runoff conditions were normal.

1.2.4 PERMANENT POOL ZONE

The Permanent Pool Zone is the bottom zone that is intended to be permanently filled with water. The zone provides for future sediment storage capacity and maintenance of minimum pool levels for power heads, irrigation diversions, water supply, recreation, water quality, and fish and wildlife. A drawdown into this zone is generally not scheduled except in unusual conditions. The Mainstem System storage capacity in this storage zone is 18.0 MAF and represents 25 percent of the total storage volume. The Permanent Pool Zone extends from 18.0 MAF down to 0 MAF.

1.2.5 WATER CONTROL PLAN FOR THE MAINSTEM SYSTEM

Variations in runoff into the Mainstem System necessitates varied regulation plans to accommodate the multipurpose regulation objectives. The two primary high-risk flood seasons are the plains snowmelt and rainfall season extending from late February through April, and the mountain snowmelt and rainfall period extending from May through July. Also, the winter ice-jam flood period extends from mid-December through February. The highest average power generation period extends from mid-April to mid-October, with high peaking loads during the winter heating season (mid-December to mid-February) and the summer air conditioning season (mid-June to mid-August). The power needs during the winter are supplied primarily with Fort Peck and Garrison Dam releases and the peaking capacity of Oahe and Big Bend Dams. During the spring and summer period, releases are normally geared to navigation and flood control requirements, and primary power loads are supplied using the four lower dams. The normal 8-month navigation season extends from April 1 through November 30, during which time Mainstem System releases are increased to meet downstream target flows in combination with downstream tributary inflows. Winter releases after the close of the navigation season are much lower and vary depending on the need to conserve or evacuate storage volumes, downstream ice conditions permitting. Releases and pool fluctuations for fish spawning management generally occur from April 1 through June. Two threatened and endangered bird species, piping plover (*Charadrius melodus*) and least tern (*Sterna antillarum*), nest on “sandbar” areas from early May through mid-August. Other factors may vary widely from year to year, such as the amount of water-in-storage and the magnitude and distribution of inflow received during the coming year. All these factors will affect the timing and magnitude of Mainstem System releases. The gain or loss in the water stored at each reservoir must also be considered in scheduling the amount of water transferred between reservoirs to achieve the desired storage levels and to generate power. These items are continually reviewed as they occur and are appraised with respect to the expected range of regulation.

1.3 DESCRIPTION OF THE GARRISON PROJECT

1.3.1 PROJECT OVERVIEW

Construction of the Garrison Project began in 1946, and closure of Garrison Dam in 1953 resulted in the formation of Garrison Reservoir (Lake Sakakawea), which is the largest Corps reservoir in the United States. Garrison Reservoir and Dam are authorized for the purposes of flood control, recreation, fish and wildlife, hydroelectric power production, water supply, water quality, navigation, and irrigation. The powerplant has five generating units. Over the period 1967 through 2007 an annual average 2.32 million megawatt hours of electricity was produced, which has a current revenue value of approximately $37 million. Habitat for two endangered species, pallid sturgeon (*Scaphirhynchus albus*) and interior least tern, and one threatened species, piping plover, occurs within the project area. The reservoir is used as a water supply by some individual cabins and by the towns of Four Bears, Mandaree, Park City, Parshall, Riverdale, Trenton, Twin Buttes, and Williston, North Dakota. Garrison Reservoir is an important recreational resource and a major visitor destination in North Dakota.

Garrison Dam is located in central North Dakota on the Missouri River at RM 1389.9, about 75 miles northwest of Bismarck, North Dakota. When full, the reservoir is 178 miles long, up to 6 miles wide, has 1,884 miles of shoreline, and contains nearly 24 million acre-ft (MAF). Table 1.1 summarizes how the surface area, volume, mean depth, and retention time of Garrison Reservoir vary with pool elevations. Major inflows to the reservoir are the Missouri River and Little Missouri River. Water discharged through Garrison Dam for power production is withdrawn from Garrison Reservoir at elevation 1672 ft-msl, approximately 2 feet above the reservoir bottom.

Garrison Reservoir first reached its minimum operating level in late 1955. Due to drought conditions it was not until 10 years later, in 1965, that the Carryover Multiple Use Zone was first filled. Generally, it remained filled from that time except for the two drought periods to date (1988 through 1993 and 2000 through present). Exclusive flood control storage space was used in 1969, 1975, 1995, and 1997. During 1975, all flood control space was filled and the maximum reservoir level was 0.8 foot above the top of the Exclusive Flood Control Zone, elevation 1854.8 feet-msl.

1.3.2 WATER QUALITY STANDARDS CLASSIFICATIONS AND SECTION 303(D) LISTINGS

1.3.2.1 Garrison Reservoir

Pursuant to the Federal Clean Water Act (CWA), the State of North Dakota has designated Garrison Reservoir as a Class 1 lake. As such, the reservoir is to be suitable for the propagation and/or protection of a coldwater fishery (i.e., salmonid fishes and associated aquatic biota); swimming, boating, and other water recreation; irrigation; stock watering; wildlife; and for municipal or domestic use after appropriate treatment. Also pursuant to the CWA, the State of North Dakota has placed the reservoir on

Table 1-1 Surface area, volume, mean depth, and retention time of Garrison Reservoir at different pool elevations. (Based on a 1988 survey of Garrison Reservoir.)

Elevation (Feet-msl)	Surface Area (Acres)	Volume (Acre-Feet)	Mean Depth (Feet)*	Retention Time (Years)**
1855	384,480	24,203,180	63.0	1.54
1850	364,265	22,331,620	61.3	1.42
1845	344,460	20,558,360	59.7	1.31
1840	320,600	18,893,560	58.9	1.20
1835	296,210	17,355,220	58.6	1.10
1830	280,520	15,916,490	56.7	1.01
1825	263,525	14,556,980	55.2	0.93
1820	249,665	13,275,410	53.2	0.85
1815	235,600	12,061,430	51.2	0.77
1810	219,955	10,921,980	49.7	0.70
1805	204,453	9,861,138	48.2	0.63
1800	188,998	8,877,219	47.0	0.57
1795	173,070	7,973,682	46.1	0.51
1790	161,295	7,139,184	44.3	0.45
1785	148,759	6,364,791	42.8	0.41
1780	138,809	5,646,736	40.7	0.36
1775	128,261	4,979,890	38.8	0.32

Average Annual Inflow (1968 through 2007) = 16.313 Million Acre-Feet

Average Annual Outflow: (1968 through 2007) = 15.53 Million Acre-Feet

* Mean Depth = Volume ÷ Surface Area.

** Retention Time = Volume ÷ Average Annual Outflow.

Note: Exclusive Flood Control Zone (elev. 1854-1850 ft-msl), Annual Flood Control and Multiple Use Zone (elev. 1850-1837.5 ft-msl), Carryover Multiple Use Zone (elev. 1837.5-1775 ft-msl), and Permanent Pool Zone (elev. 1775-1670 ft-msl).

the State's Section 303(d) list of impaired waters citing impairment to the uses of fish and other aquatic biota and fish consumption due to the pollutants/stressors of low dissolved oxygen, water temperature, and methyl-mercury. The State of North Dakota has issued a fish consumption advisory for Garrison Reservoir due to mercury concerns.

1.3.2.2 Missouri River Downstream of Garrison Dam

The State of North Dakota has designated the entire Missouri River as a Class I stream. As such, the river is to be suitable for the propagation and/or protection of resident fish species and other aquatic biota; swimming, boating, and other water recreation; irrigation; stock watering; wildlife; and for municipal or domestic use after appropriate treatment. The river has not been placed on the State's Section 303(d) list of impaired waters. The State of North Dakota has issued a fish consumption advisory for the Missouri River due to mercury concerns.

1.3.3 OCCURRENCE OF A "TWO-STORY" FISHERY

Garrison Reservoir maintains a "two-story" fishery comprised of warmwater and coldwater species. The ability of the reservoir to maintain a "two-story" fishery is due to its thermal stratification in the summer into a colder bottom region and a warmer surface region. Warmwater species present in Garrison Reservoir that are recreationally important include walleye (*Sander vitreus*), sauger (*Sander canadensis*), northern pike (*Esox lucius*), smallmouth bass (*Micropterus dolomieu*), catfish (*Ictalurus spp.*), and yellow perch (*Perca flavescens*). A coldwater species of recreational importance is the Chinook salmon (*Oncorhynchus tshawytscha*). Chinook salmon are maintained in Garrison Reservoir through regular stocking. Another coldwater species present in the reservoir is the rainbow smelt (*Osmerus mordax*). This species is an important forage fish that is utilized extensively by all recreational species in the reservoir. Maintaining healthy populations of these coldwater forage fish are important to maintaining the recreational fisheries in Garrison Reservoir.

The occurrence of coldwater habitat (CWH) in Garrison Reservoir is directly dependent on the reservoir's annual thermal regime. Early in the winter ice-cover period, the entire reservoir volume will be supportive of CWH. As the winter ice-cover period continues, lower dissolved oxygen concentrations will likely occur near the bottom as organic matter decomposes and reservoir mixing is prevented by ice cover. As dissolved oxygen concentrations in the near-bottom water fall below 5 mg/l, CWH will not be supported. During the spring isothermal period, water temperatures and dissolved oxygen levels in the entire reservoir volume will be supportive of CWH. During the early-summer warming period, the epilimnion will become non-supportive of CWH. During mid-summer when the reservoir is experiencing maximum thermal stratification, water temperatures will only be supportive of CWH in the hypolimnion. Theoretically, CWH should remain stable during this period unless degradation of dissolved oxygen concentrations near the reservoir bottom becomes non-supportive of CWH. The most crucial period for the support of CWH in Garrison Reservoir is when it begins to cool in late summer. As the thermocline moves deeper, the volume of the coldwater hypolimnion will continue to decrease while the expanding epilimnion may not yet be cold enough to be supportive of CWH. At the same time, hypolimnetic dissolved oxygen concentrations are approaching their maximum degradation and low dissolved oxygen levels are moving upward from the reservoir bottom and pinching off CWH from below. This situation will continue to worsen until the epilimnion cools enough to be supportive of CWH. When fall turnover occurs, dissolved oxygen concentrations at all depths will be near saturation and supportive of CWH. However, depending on the conditions of the reservoir, the isothermal temperature at the beginning of fall turnover may not be supportive of all CWHs. This situation will continue to occur until the isothermal temperature cools to suitable temperatures, at which time the entire reservoir volume will be supportive of CWH.

1.4 IMPLEMENTATION OF SHORT-TERM WATER QUALITY MANAGEMENT MEASURES TO ENHANCE COLDWATER FISHERY HABITAT IN GARRISON RESERVOIR

As drought conditions persisted in early 2005, water levels in Garrison Reservoir had fallen to a record low pool elevation of 1805.8 feet-msl on May 12, 2005. At that time it was felt that unless emergency water quality management measures were implemented in 2005 to preserve the CWH in the reservoir, the recreational sport fishery would likely be adversely impacted. The reduction of CWH is exacerbated by withdrawals through the Garrison Dam intake structure. Because the invert elevation of the intake portals to the Garrison Dam power tunnels (i.e., penstocks) is 2 feet above the reservoir bottom, water drawn through the penstocks comes largely from the lower depths of the reservoir. Thus, during the summer thermal-stratification period, water is largely drawn from the hypolimnetic volume of Garrison Reservoir. Three short-term water quality management measures were identified for implementation in 2005 in an effort to preserve the CWH in the reservoir. These measures, which were implemented at Garrison Dam, included: 1) application of a plywood barrier to the dam's intake trash racks, 2) utilization of head gates to restrict the opening to the dam's power tunnels, and 3) modification of the daily flow cycle and minimum flow releases from the dam. The three implemented water quality management measures were targeted at drawing water into the dam from higher elevations within Garrison Reservoir.

1.4.1 APPLICATION OF A PLYWOOD BARRIER TO THE DAM'S INTAKE TRASH RACKS

The five power tunnels at Garrison Dam are screened at the upstream end of the water passage by trash racks. These trash racks prevent large objects from entering the penstocks and causing serious damage to the wicket gates and turbine. Each of the five penstocks has two intake passages for a total of ten intakes. The trash rack for each of the ten intakes consists of seven separate frame sections. The trash rack fits into the trash rack slots at the front of the intake passage piers. A hook for each rack is fixed to the top of the frame. A lifting beam and mobile crane is used to raise and lower each trash rack.

The existing trash racks were modified to raise the elevation where water was withdrawn from Garrison Reservoir. The trash rack modification consisted of installing plywood sheathing on the upstream side of the existing trash rack grates on the power tunnels to Units 1, 2, and 3. The plywood sheathing was applied to the trash racks to Units 2 and 3 in July 2005 and on the trash racks to Unit 1 in May 2007. On Units 2 and 3, the plywood sheathing covers the lower 48 feet of the trash racks (i.e., approximately elevation 1672 to 1720 ft-msl) with the exception of a 3-inch slot at the very bottom for passing sediments. Due to a large tree at the bottom of the east intake to Unit 1, plywood could not be installed on all the trash racks. The bottom trash rack on the east side of Unit 1 could not be removed and did not receive a plywood barrier. There are 2½ trash racks with plywood barriers on the east side of Unit 1 and 3½ trash racks with plywood on the west side. Therefore, the plywood barrier on the west side of Unit 1 extended from elevation 1672 to 1720 ft-msl, and on the east side of Unit 1 from elevation 1688 to 1720 ft-msl. The plywood on Units 2 and 3 was inspected with an underwater camera in the spring of 2006 and 2007 and determined to still be in good condition.

1.4.2 UTILIZATION OF HEAD GATES TO RESTRICT THE OPENING TO THE DAM'S POWER TUNNELS

Each of the intake passages to all five power tunnels have operational head gates that control flow into the tunnels. It was reasoned that lowering one of the two head gates to block a single passage to the power tunnel should increase the velocity of water drawn into the power tunnel, given the total flow through the power tunnel remained the same. Increasing the velocity of the water drawn into the intake could pull water from a higher elevation in Garrison Reservoir and possibly help maintain the reservoir's deeper, colder volume. To implement this measure in 2006 and 2007, single head gates on the passages to penstocks 1 and 4 were lowered, respectively, on July 5, 2006 and May 30, 2007.

1.4.3 MODIFICATION OF DAILY FLOW CYCLE AND MAXIMUM AND MINIMUM FLOW RELEASES

Past water quality monitoring at the Garrison Dam powerhouse indicated that the vertical extent of the withdrawal zone in Garrison Reservoir, during summer thermal stratification, was dependent on the discharge rate of the dam. Warmer water high in dissolved oxygen was drawn down from higher elevations in the reservoir under higher discharge rates, and colder water low in dissolved oxygen was drawn from the lower depths of the reservoir under lower discharge rates. The influence of the dam's discharge rate on the reservoir withdrawal zone is believed to be partly attributed to the design of the intake structure and submerged intake channel.

To the extent possible, flow releases from Garrison Dam during 2005, 2006, and 2007 were modified to try to maximize the water drawn from higher elevations and minimize the water drawn from lower elevations in Garrison Reservoir. The following two flow release modifications were pursued: 1) daily flow releases should be in either a maximum or minimum mode; and 2) minimum flows should be discharged through the Units which have the plywood barriers in place.

1.5 AMBIENT WATER QUALITY MONITORING AT THE GARRISON PROJECT

The District has monitored water quality conditions at the Garrison Project since the late 1970's. Water quality monitoring locations have included sites on the reservoir and on the inflow to and outflow from the reservoir. A 3-year intensive water quality survey was conducted at the Garrison Project during 2003 through 2005. Figure 1.1 shows the location of sites at the Garrison Project that were monitored for water quality during the period 2003 through 2007. The near-dam location (i.e., site GARLK1390A) has been continuously monitored since 1980.

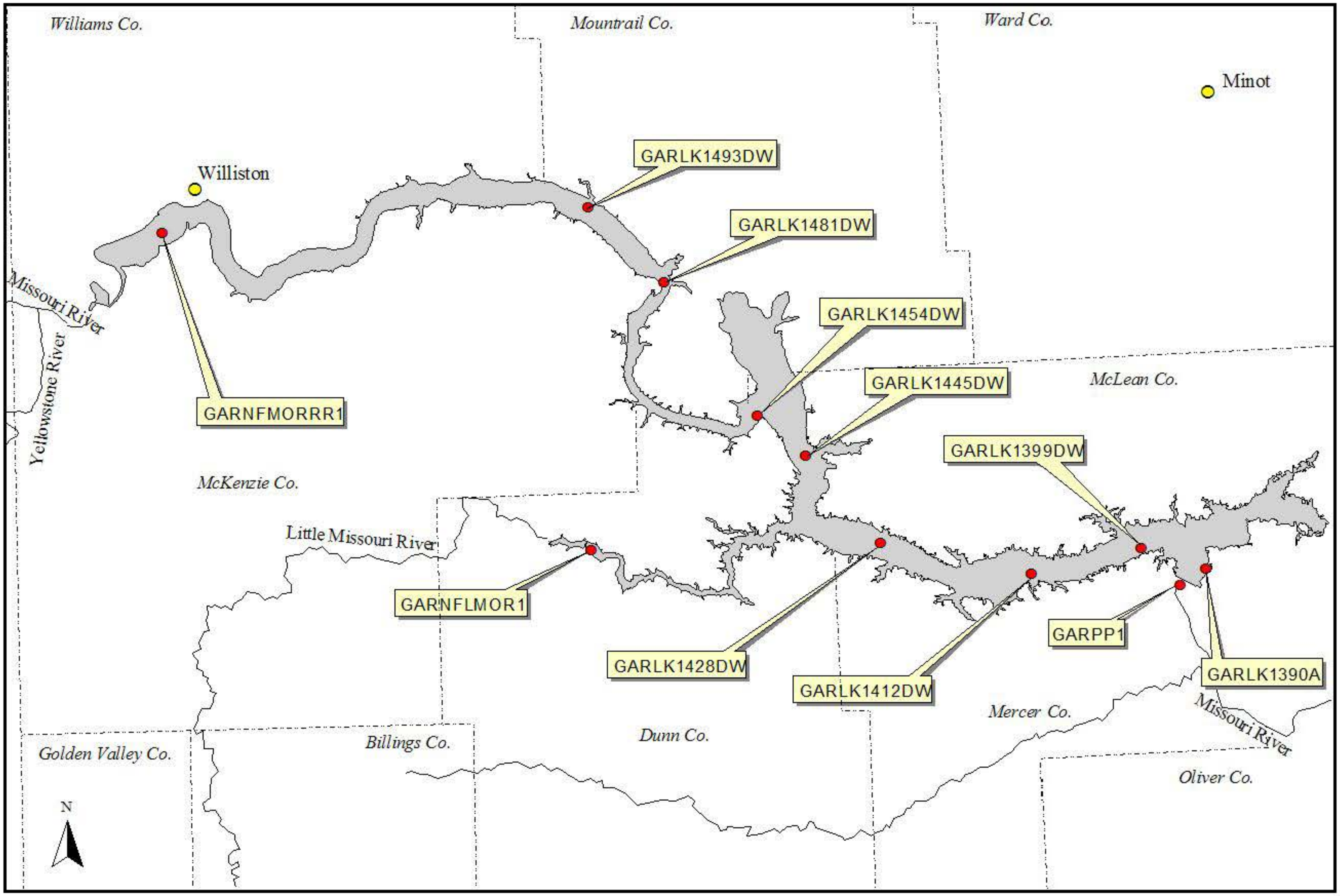


Figure 1-1. Location of sites where water quality monitoring was conducted by the District at the Garrison Project during the period of 2003 through 2007.

2 MODEL METHODS, SETUP & DATA

2.1 CE-QUAL-W2

CE-QUAL-W2 is a two-dimensional (longitudinal and vertical) water quality and hydrodynamic model for rivers, estuaries, lakes, reservoirs, and river basin systems. CE-QUAL-W2 simulates basic physical, chemical, and biological processes such as temperature, nutrient, algae, dissolved oxygen, organic matter, and sediment relationships. The model is supported by the Environmental Lab at the USACE Engineering Research and Development Center (ERDC) Waterways Experiment Station (WES) in Vicksburg, MS, and by the Civil Engineering Department at Portland State University in Portland, OR.

Version 2.0 of the CE-QUAL-W2 model was applied to four of the upper Mainstem System Projects in the early 1990s (i.e., Ft. Peck Lake, Lake Sakakawea, Lake Oahe, and Lake Francis Case). The application of the model was part of the supporting technical documentation of the Environmental Impact Statement (EIS) that was prepared for the Missouri River Master Water Control Manual Review and Update Study. The results of the model application were included as an Appendix to the Review and Update Study – "Volume 7B: Environmental Studies, Reservoir Fisheries, Appendix C – Coldwater Habitat Model, Temperature and Dissolved Oxygen Simulations for the Upper Missouri River Reservoirs" (Cole et. al., 1994).

The Version 3.2 was used to model temperature, dissolved oxygen, and nutrients in Lake Sakakawea. Predicted temperatures in the lake will be influenced by reservoir inflow volumes and temperatures; environmental factors such as wind, air temperature, and solar radiation; and management factors such as reservoir release rates and outflow structure configurations.

All model calculations and outputs are performed in the International System (SI) of Units; therefore, all subsequent data and figures presented in this report are expressed in SI units with the exception of coldwater habitat which is expressed in traditional English units of acre feet.

2.2 HYDRODYNAMICS

The governing equations for hydrodynamics and transport are derived from the conservation of fluid mass and momentum equation. The model uses a hydrostatic approximation for vertical fluid movement rather than rely on the true conservation of momentum equation. Hydrodynamics and transport are laterally and layer averaged meaning lateral and layer variations in velocities, temperatures and constituents are negligible. The hydrodynamic behavior of the model is dependent largely on initial conditions, boundary conditions, and hydraulic conditions which are described with specific regard to the Lake Sakakawea model in the following paragraphs and later sections of this report.

2.2.1 INITIAL CONDITIONS

Annual simulations were performed from January 1 (jday = 1) to December 31 (jday = 365) with a minimum timestep of 1 minute. The initial water column temperature was set to 1.0 degrees C, which is approximately the average simulated water temperature at the end of the simulation year. An initial ice thickness of 0.28 meters (0.9 ft) covering the entire reservoir on January 1 was assumed in all simulation years.

2.2.2 HYDRAULIC COEFFICIENTS

CE-QUAL-W2 uses default values for a number of hydraulic parameters that influence the movement of momentum and heat exchange within a water body (Table 2-1). The horizontal dispersion of momentum and heat are determined by the horizontal eddy viscosity and diffusivity, while vertical diffusion of momentum is influenced by the method for computing the vertical eddy viscosity. A very important factor influencing momentum transfer and mixing near the bottom of a water body is the bottom friction expressed either as Manning's roughness or Chezy coefficients. In the Lake Sakakawea model, Chezy coefficients ranging from 70 to 90 were used throughout the entire water body.

Table 2-1. CE-QUAL-W2 hydraulic and heat exchange coefficients.

Hydraulic Coefficients	
Horizontal Eddy Viscosity & Diffusivity (m^2/s)	1.0
Vertical Eddy Viscosity Method	W2
Max. Vertical Eddy Viscosity (m^2/s)	0.001
Friction Type (Chezy)	70 - 90
Heat Exchange Coefficients	
Sediment Heat Exchange Coefficient (W/ m^2/s)	0.3
Bottom Sediment Temperature (^oC)	10
Fraction Solar Radiation at Sediment to Water	0.25
Coefficient of water-ice heat exchange	10
Ice Albedo (Reflection/Incident)	0.25
Fraction of Radiation Absorbed by Ice	0.6
Solar Radiation Extinction Coefficient (m^{-1})	0.07
Temperature for ice formation (^oC)	3.0
Wind Measurement Height (m)	3.0
Fraction of solar radiation absorbed at WS	0.4

2.2.3 HEAT EXCHANGE

Water surface heat exchange is defined as the sum of incident short and long wave solar radiation, reflected short and long wave solar radiation, back radiation, evaporative heat loss, and heat conduction. Since some of these computed terms are temperature dependent, the Lake Sakakawea model uses an equilibrium temperature method in which the net rate of surface heat exchange is zero at the equilibrium temperature. Although this method is empirical in nature, it consistently gives better results than other theoretical methods. A number of heat exchange coefficients that affect ice formation and transfer of heat through ice are specified in Table 2-1.

Heat is transferred between the bottom sediment-water interface, and a heat exchange rate along with average sediment temperature must be specified. The fraction of solar radiation re-radiating from the lake bottom to the water column is specified as a fraction of radiation reaching the bottom. In Lake Sakakawea very limited shortwave solar radiation reaches the bottom.

The wind measurement height is particularly important because the model adjusts wind speed to the height of the wind speed formulation which drives surface mixing and evaporative heat losses. In addition the fraction of solar radiation absorbed by the water surface is specified.

2.3 WATER QUALITY

CE-QUAL-W2 computes numerous water quality constituents in their basic forms and derived forms based on a constituent mass balance. Within this mass balance constituents may undergo kinetic reactions that convert the nutrient to other organic or inorganic forms of the nutrient by algae utilization or other biological processes. While nutrients are important in many water quality applications, dissolved oxygen is a more important parameter concerning Lake Sakakawea.

2.3.1 NUTRIENTS

Lake nutrients undergo transport and kinetic reactions through biological or chemical transformation to nutrient sources or sinks. Water quality state variables used in the Lake Sakakawea simulations included total dissolved solids (TDS), suspended solids (SS), bio-available phosphorus, ammonium, nitrate-nitrite, dissolved and particulate silica, total iron, labile and refractory forms of dissolved and particulate organic matter, algae, dissolved oxygen (DO), total inorganic carbon, and alkalinity. Further discussion on how CE-QUAL-W2 handles nutrient kinetics may be found in the Appendix B of the User Manual (Cole and Wells, 2003).

2.3.2 DISSOLVED OXYGEN

A use of the water quality constituent modeling is to compute cold water habitat as a function of dissolved oxygen (and temperature) throughout the reservoir. The most important components that serve as sources of dissolved oxygen in these simulations are aeration from the atmosphere and algae (phytoplankton) photosynthesis, depicted in Figure 2-1. Dissolved oxygen sinks include algal respiration and decay or decomposition of organic sediments and organic matter. Reaeration, organic matter oxygen demand, algal dynamics, and sediment oxygen demand are discussed in more detail.

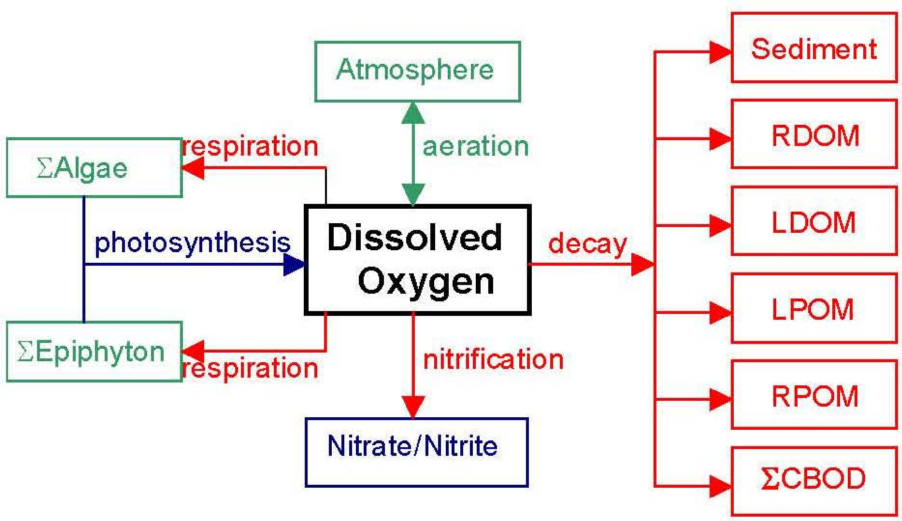


Figure 2-1. Dissolved oxygen dynamics in CE-QUAL-W2.

2.3.2.1 <u>Reaeration</u>

The reaeration of water with dissolved oxygen occurs in lakes as a function of turbulent mixing caused by surface winds. Reaeration by wind primarily effects dissolved oxygen concentrations in the mixed volume of the water column (e.g., epilimnion during summer thermal stratification, etc.). Model equations are written for 10-meter measured wind heights, but can be adjusted for alternate wind heights.

2.3.2.2 <u>Organic Matter</u>

The total oxygen demand exerted on a lake is often measured as biological oxygen demand (BOD); however, both decomposition and production of these materials occurs in the model so organic matter represented as BOD must be separated into its major components, which include labile dissolved organic matter (LDOM), refractory dissolved organic matter (RDOM), labile particulate organic matter

(LPOM), and refractory particulate organic matter (RPOM). Dissolved organic matter (DOM) and particulate organic matter (POM) are important because they utilize dissolved oxygen (DO) during their decay process. Labile DOM and labile POM decays at a faster rate than refractory OM, which is product of labile OM decay. Settling POM contributes to the lake sediment oxygen demand. DOM and POM are produced by algae mortality and excretion. DO concentrations in the reservoir are greatly influenced by organic matter (OM) dynamics. Initial and observed OM concentrations in the lake and inflows were estimated based on measured concentrations of total organic carbon (TOC).

2.3.2.3 Algal Dynamics

Although CE-QUAL-W2 version 3.2 allows algal groups to be broken into several types of algae, one algal group representing both blue-green algae and diatoms was modeled. Algae are important in nutrient and DO dynamics by utilizing nutrients and producing DO during photosynthesis, and utilizing DO during respiration. Algal mortality and excretion produces DOM and POM which eventually decay and further utilize DO. Chlorophyll *a* (Chl *a*) may be used as an indicator of algae present in the reservoir.

2.3.2.4 Sediment Oxygen Demand

Organic sediments resulting from algae and OM decay contribute to nutrients and DO demand in the reservoir using a constant (zero-order) release and demand method, and an organic sediment accumulative (first-order) method. The zero-order method specifies a sediment oxygen demand (SOD) and nutrient release rates that are temperature dependent. The first-order method accumulates organic sediment from settling of algae and POM, therefore it is more predictive in nature and attempts to accurately account for the SOD. Both zero- and first-order SOD methods are used concurrently in the water quality simulations.

2.3.3 INITIAL CONDITIONS

Initial constituent concentrations were derived from minimum constituent concentrations detected in the ambient water quality samples from the reservoir, with the exception of dissolved oxygen (DO), labile dissolved organic matter (LDOM), and labile particulate organic matter (LPOM). The year end simulated average DO concentration in the reservoir was substituted for the initial DO concentration in the subsequent year. LDOM and LPOM initial concentrations were determined the same way.

2.4 MODEL SETUP

2.4.1 LAKE BATHYMETRY

The Lake Sakakawea bathymetry was modified from the bathymetry used in the Coldwater Habitat Model constructed by Cole et al. (1994) of the U.S. Army Corps of Engineers Waterways Experiment Station in Vicksburg, MS. The reservoir bathymetry consisted of one main branch with three minor branches, and it is shown in Figure 2-2. Branch 1 of the model is the main Missouri River branch, and it contains 55 active segments and 29 layers. Branch 2 represents the Van Hook Arm of the lake southeast of the Four Bears Bridge and New Town, ND. Branch 3 is the Little Missouri River arm of the lake. Branch 4 is a shallower extension of the main channel that terminates at the Lake Audubon dam. Bathymetry for the minor branches was developed from the 1987 sediment range survey cross sections. All bathymetry segments are 5 km (3.1 mi) in length with 2 m (6.56 ft) vertical layer thicknesses. The length of the lake bathymetry from inlet to outlet is 275 km (170.9 mi) and the lake model depth at the dam is 58 m (190.3 ft). At the top of the flood control and multipurpose pool level at

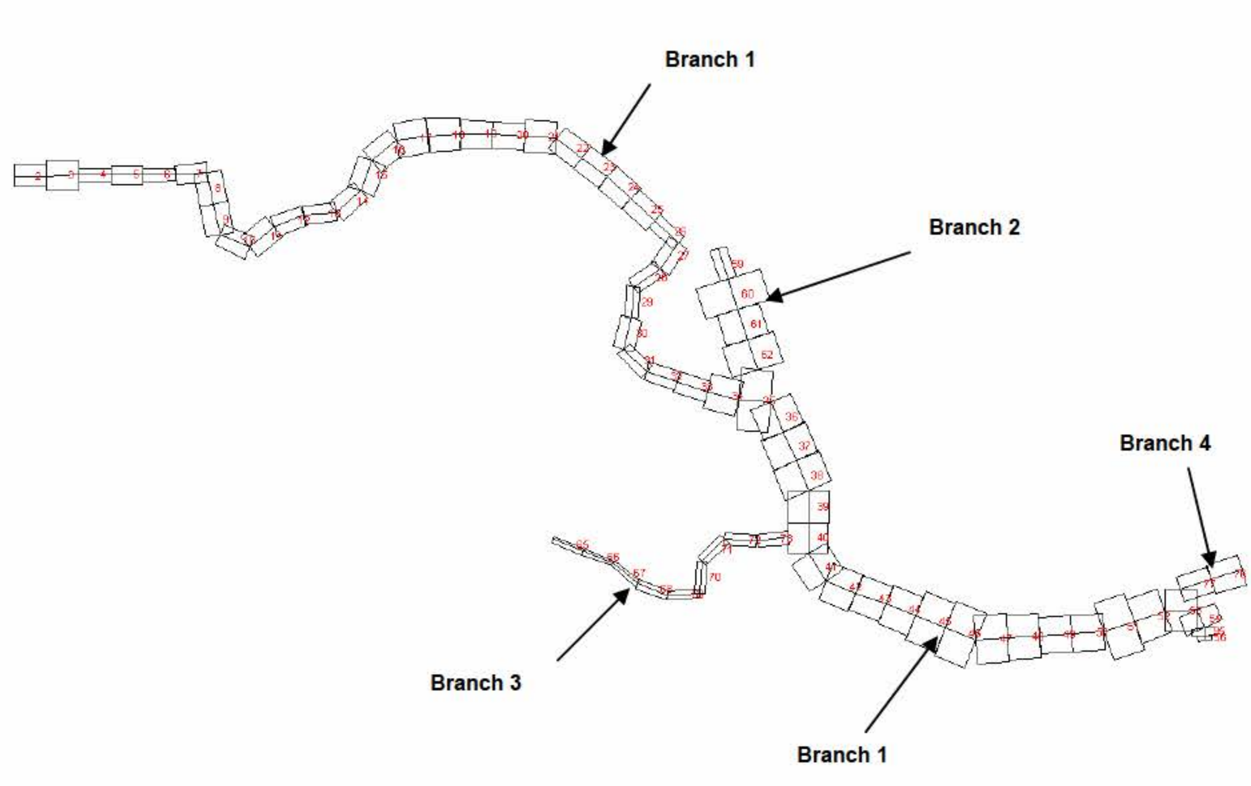


Figure 2-2. Plan view of the Lake Sakakawea water body branches, segment layout, and orientation in space.

elevation 563.9 m (1850 ft) segment widths ranged from 924 m (3,301 ft) to 9,766 m (32,041 ft). Chezy's bottom friction coefficients ranged from 70 to 90.

Volume-area-elevation curves constructed from the Corps of Engineers survey and computed from model bathymetry are compared in Figures 2-3 and 2-4. Minor adjustments were made to the bathymetry in order to improve the accuracy of the model lake area and volume. The model and COE surveyed lake areas deviate some, yet the volumes match closely. At the top of the flood control and multipurpose pool elevation the model lake volume is 27,571 million m^3 (22.4 million ac ft), and at the bottom of the flood control and multipurpose pool elevation (560.1 m) the model lake volume is 22,327 million m^3 (18.1 MAF).

In the initial simulations temperatures in the hypolimnion were colder than observed, so in order to warm them, the hypolimnetic volume was reduced. This was accomplished along the lake profile by eliminating 2 to 4 meters of bottom depth and reducing layer widths in the remaining bottom 4 to 8 meters. Reducing the hypolimnetic volume had a limited effect on the shape of the temperature profile, while temperatures in the entire hypolimnion were warmed.

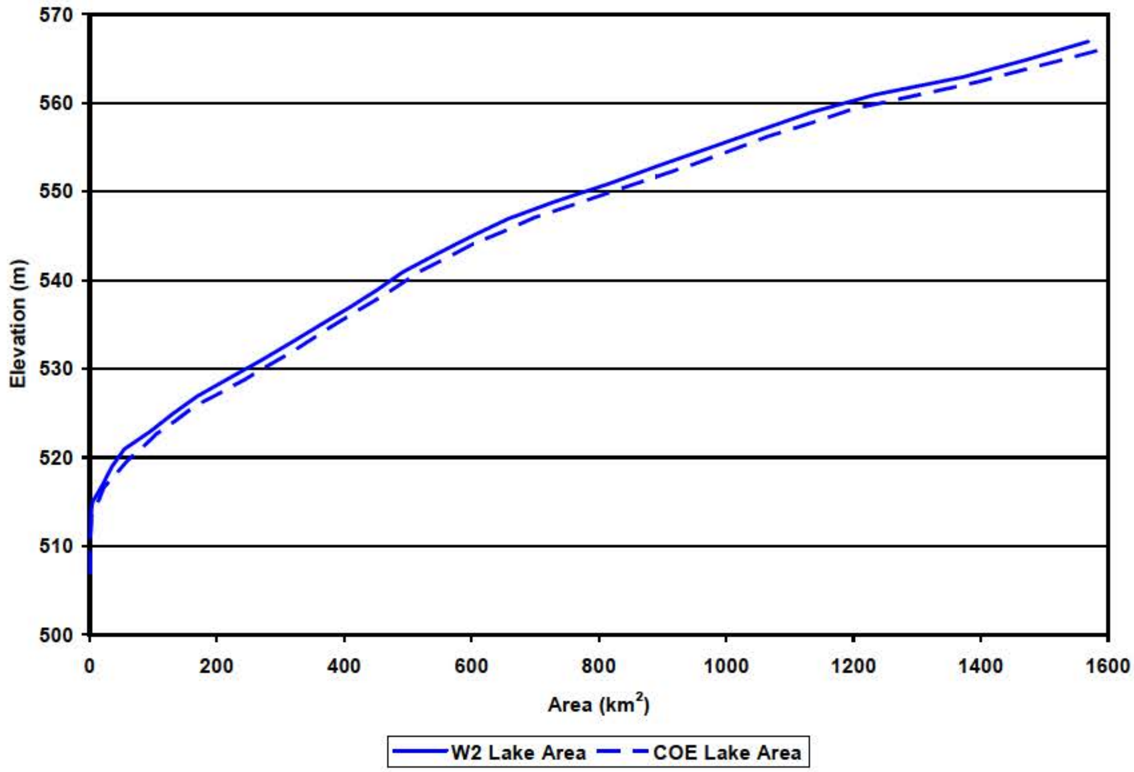


Figure 2-3. Area-elevation curves computed from the W2 model bathymetry and the 1987 COE lake survey.

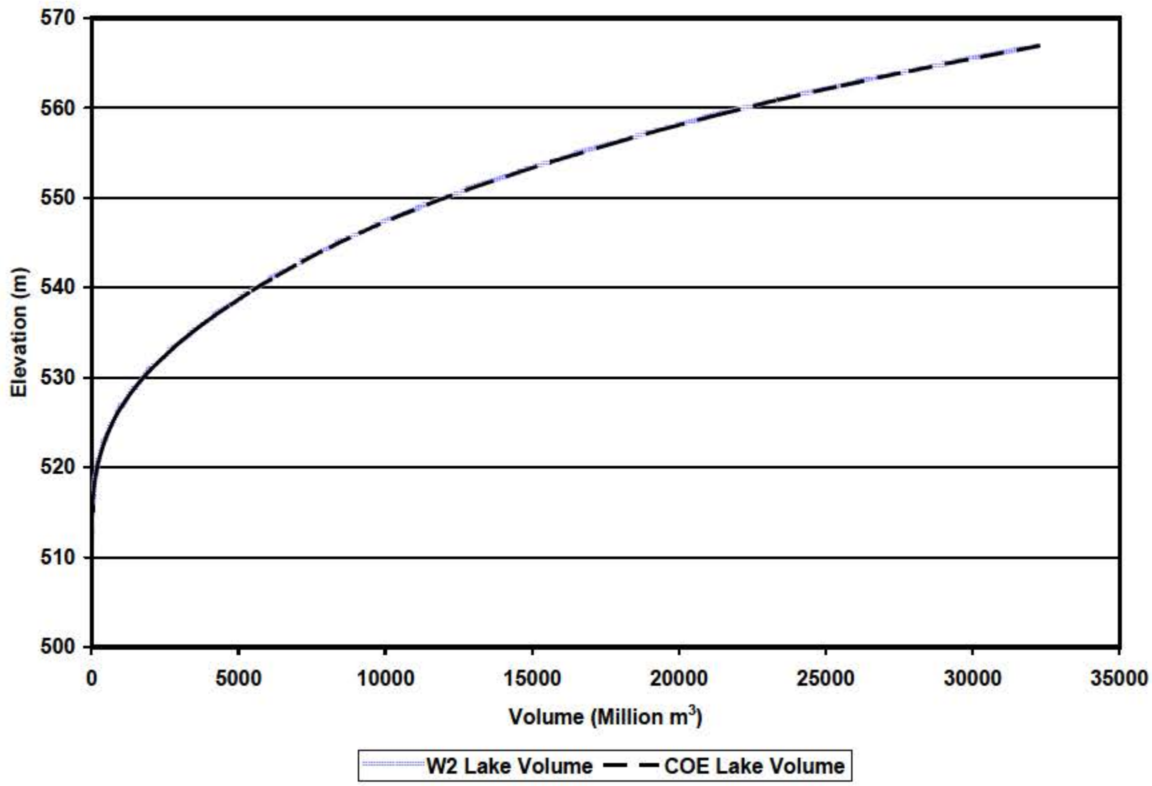


Figure 2-4. Volume-elevation curves computed from the W2 model bathymetry and the 1987 COE lake survey.

2.4.2 INTAKE STRUCTURE CHANNEL

The lake was constructed with a 142 m (470 ft) wide submerged intake channel extending nearly 3,505 m (11,500 ft) from the original Missouri River channel to the outlet works intake tower. This intake channel creates a complex situation that limits the withdrawal of water into the bottom reservoir outlet through a very narrow passage in the final model segment. During low flow releases it is hypothesized that cold water from the hypolimnion and below the thermocline is drawn along the intake channel into the intake tower. During high flows it is hypothesized that warm water is also drawn from above the thermocline during stratification due to the limits of the intake channel.

Using recent bathymetric surveys along the dam, a simple representation of the intake bathymetry was developed to better represent outlet conditions. The intake segment of the model was subdivided into three segments which possess progressively narrowing bottom widths that represented the intake channel. Segment widths are provided in Table 2-2.

Table 2-2. Submerged outlet channel W2 bathymetry for Lake Sakakawea.

Layer Bottom Elevation meters above MSL	Segment width, meters		
	Segment = 54 Length = 3000 m	Segment = 55 Length = 1200 m	Segment = 56 Length = 800 m
566.93	6073	4096	2138
564.93	5492	3935	2014
562.93	5614	3758	1886
560.93	5420	3536	1781
558.93	5098	3338	1652
556.93	4952	3217	1569
554.93	4940	3117	1505
552.93	4917	3010	1459
550.93	4914	2830	1410
548.93	4894	2584	1372
546.93	4887	2523	1301
544.93	4826	2468	1239
542.93	4804	2406	1186
540.93	4706	2288	1123
538.93	4693	2107	1072
536.93	4624	2010	1061
534.93	4441	1658	869
532.93	4329	1554	719
530.93	4284	1548	560
528.93	3920	1104	205
526.93	3748	813	188
524.93	3739	539	186
522.93	2903	196	173
520.93	2579	177	165
518.93	1800	163	156
516.93	1300	144	142
514.93	250	108	142
512.93	99	75	142
510.93	57	51	142

2.4.3 OUTLET CONFIGURATION

The intake tower and outlet works of Lake Sakakawea consists of five power tunnels and three flood control regulating tunnels with an invert elevation of 509.6 m (1672 ft). Each tunnel contains two intake portals. The intake portals on the intake towers are covered with trash racks that extend from elevation 509.6 m (1672 ft) to 540.1 m (1772 ft), and the power tunnels are 7.92 m (26 ft) in diameter. A powerhouse intake tower section is provided in Figure 2-6.

The modeled outlet is configured as a 142-meter wide line sink at centerline elevation 513.6 m (1685.0 ft). The bottom withdrawal limitation is 508.9 meters and the top limitation is 566.9 m, however the model's internal selective withdrawal algorithm determines what layers water is withdrawn from within the withdrawal limits and near the centerline elevation.

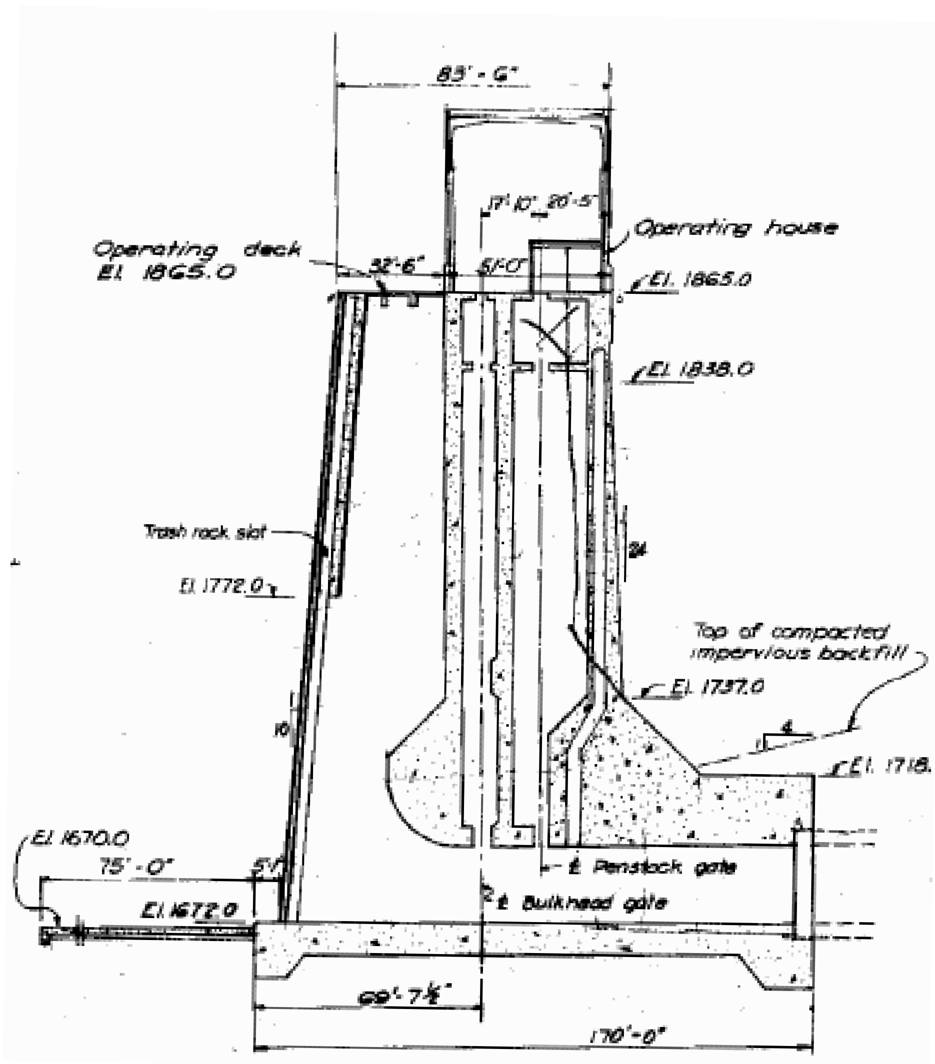


Figure 2-5. Powerhouse intake tower section.

2.4.4 OUTLET MODIFICATION

In 2005 modifications were made to the trash racks and the head gates on the intake tunnels for the purpose of limiting the withdrawal of cold water from lower levels of the reservoir. In addition flows through the penstocks were maximized and minimized in order to take advantage of the selective withdrawal of water through the towers with plywood barriers in place.

2.4.4.1 Plywood Trash Rack Barriers

Plywood barriers were fastened to the trash racks on Intake Towers 2 and 3 covering the lower 14.6 meters (48 ft) extending up to elevation 524.3 m (1720 ft) leaving 0.08 m (3 in) of clearance at the bottom of the intake tunnels for sediment passage. The trash racks with plywood covers were positioned on Tower 3 over both portals on July 15, 2005 (Jday = 196) and on Tower 2 on July 20, 2005 (Jday = 201). On May 14, 2007, attempts were made to install plywood barriers on Tower 1; however, due to debris at the bottom of the east intake portal, barriers were installed from elevation 514.5 to 524.3 meters (1688 to 1720 ft) on the east intake portal and from elevation 509.6 to 524.3 meters (1672 to 1720 ft) on the west intake portal, covering 83 percent of the entire Tower 1 intake.

2.4.4.2 Lowered Head Gates

In order to increase the velocity of water entering into the remaining power tunnels and possibly draw water from higher reservoir elevations, one of the head gates on the remaining intake towers was lowered. In 2005 one of the head gates on Tower 1 was lowered on August 18 and one of the head gates on Tower 4 was lowered on September 1. This was performed again on May 30, 2007 on the east head gates on Towers 4 and 5.

The CE-QUAL-W2 model does not possess the ability to increase water velocities through the intake towers by lowering head gates because the outlet could not be modeled with that degree of detail. Also the outlet behaves as a very small sink in relation to the width of the reservoir, and the model is laterally averaged, so no modification could be made for this condition.

2.4.4.3 Flow Modification

During flow peaking season, powerhouse discharges were fluctuated by opening and closing gates in Towers 1, 2 and 3. Minimum discharges were achieved by releasing from Towers 2 and 3, while maximum discharges were achieved by releasing from Towers 1, 2 and 3. Individual tower (penstock) discharges were entered as Lake Sakakawea discharges in the model.

2.5 MODEL INPUTS

2.5.1 METEOROLOGICAL DATA

CE-QUAL-W2 requires meteorological inputs including air temperature, dew point temperature, wind speed, wind direction, cloud cover and shortwave solar radiation. Cloud cover is used to estimate the amount of shortwave solar radiation reaching the water surface; however, it may be measured directly. Hourly weather data that included all parameters except cloud cover was obtained from the North Dakota Agricultural Weather Network (NDAWN) at research site near Plaza, ND. The station coordinates are 47°53’N latitude, 101°57’W longitude, at a ground elevation of 645.3 m (2117 ft).

2.5.1.1 Temperature

The Plaza, ND, NDAWN weather station is the most centrally located and appropriate station selected from several stations in the area including the National Weather Service automated weather station and the Garrison automated weather station. Ambient air and dew point temperatures from 2003 through 2007 are plotted in Figures 2-6 and 2-7.

2.5.1.2 Wind Data

Wind data is a major driving factor of temperature calibration, thus weather data recorded at the Plaza, Williston, and Garrison stations were examined during temperature model calibration. NDAWN Plaza, ND, data measured at an elevation of 3.0 meters was utilized in the 2003 through 2007 simulations, and average daily and maximum daily wind speeds are plotted in Figure 2-8.

2.5.1.3 Solar Radiation

Cloud cover data was quite limited in this study; only Williston and Minot NWS weather stations provided empirical cloud cover which then must be converted to cloud cover on a 1.0 to 10.0 scale. In addition, the accuracy of cloud cover, which limits incoming solar radiation and inhibits the escape of outgoing long-wave radiation, was questionable due to the local nature of the cloud cover readings and the subjectivity of the methodology for interpreting cloud cover from cloud cover readings.

Rather than allow the model to estimate incoming solar radiation from cloud cover, shortwave solar radiation, which represents mainly the visible spectrum, was used in the model. The NDAWN weather station at Plaza, ND, measures total solar radiation, but since a large percentage of total solar radiation is shortwave solar radiation, total solar radiation measurements were reduced by 5 to 15 percent in order to represent shortwave solar radiation. Short-wave solar radiation estimated from total solar radiation is plotted in Figure 2.9.

2.5.1.4 Wind Sheltering Coefficients

Wind sheltering coefficients are the ratio of transferred wind energy to actual wind energy present in the meteorological data. Wind sheltering coefficients are one of the most important calibration parameters because they directly influence the amount of mixing that occurs in the surface layer of the reservoir and therefore the transfer of heat energy from the water surface to deeper layers in the reservoir. Wind sheltering coefficients ranging from 0.9 to 1.1 were used in the model.

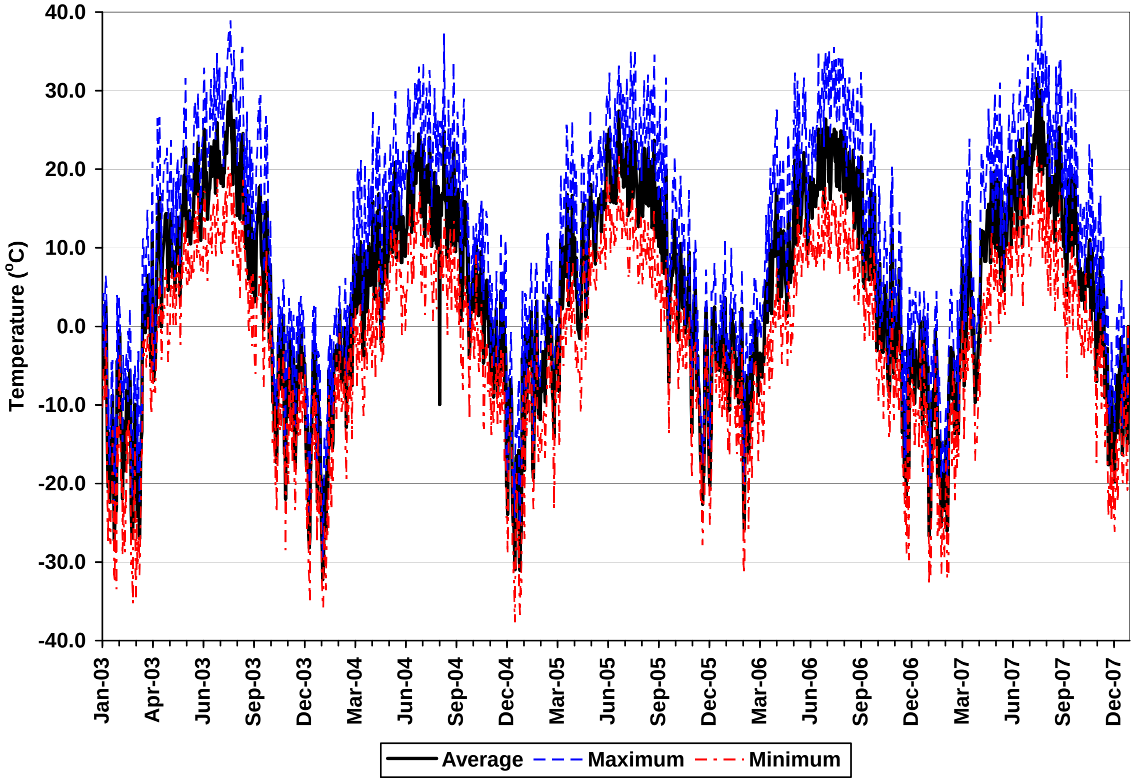


Figure 2-6. Daily average, maximum, and minimum air temperatures at Plaza, ND.

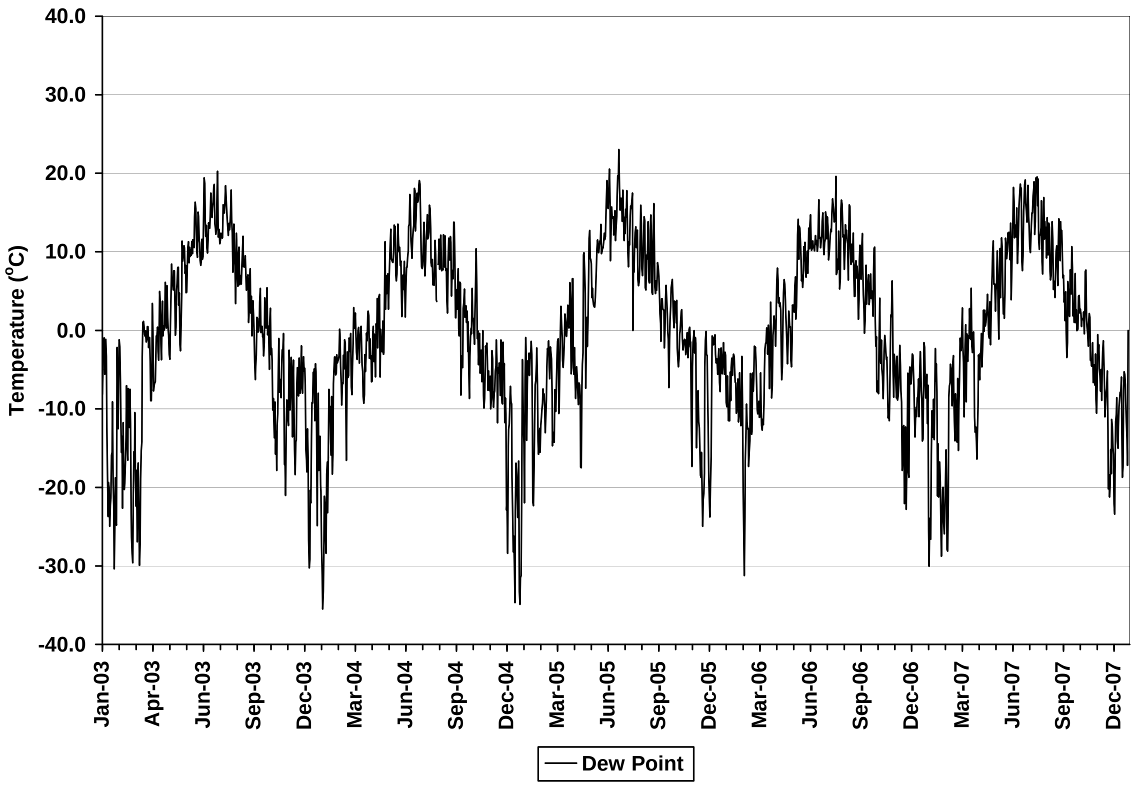


Figure 2-7. Daily average dew point temperature at Plaza, ND.

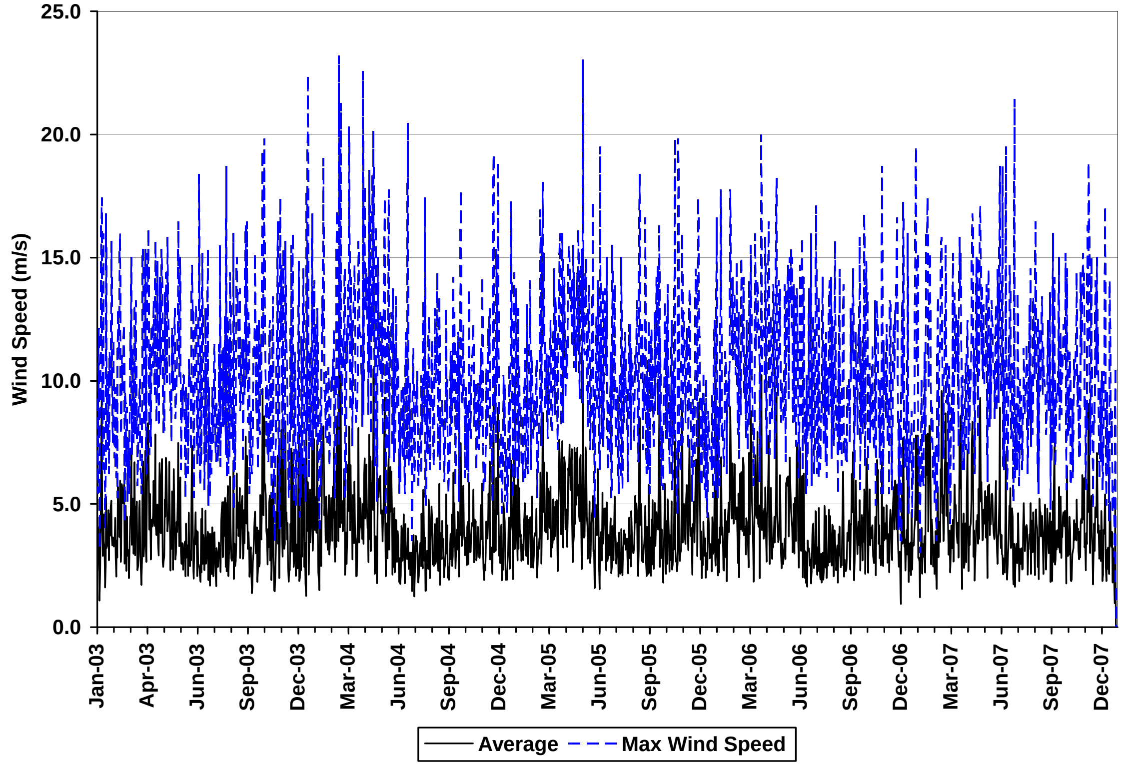


Figure 2-8. Daily average and maximum wind speed at Plaza, ND.

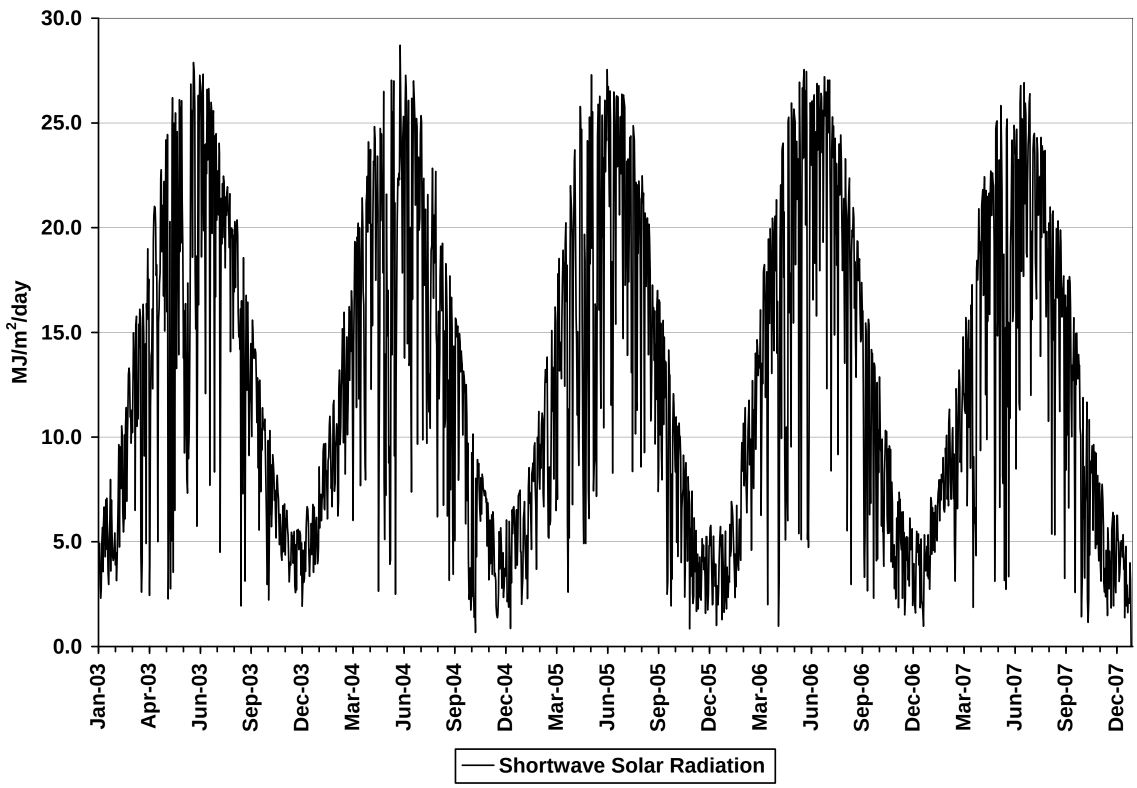


Figure 2-9. Approximated daily average shortwave solar radiation at Plaza, ND.

2.5.2 RESERVOIR INFLOW AND OUTFLOW

Daily inflow from the Missouri and Little Missouri Rivers were input as reservoir branch inflows while several minor tributaries were excluded from the model. Daily Missouri River inflow was computed by subtracting daily Little Missouri River inflows from daily inflows computed by the Corps of Engineers Northwest Division Missouri River Reservoir Control Center. Little Missouri River daily inflows were measured by the USGS at Watford City, ND (Gage no. 06337000). Daily inflows are plotted in Figure 2-10.

Daily and hourly reservoir outflow data for each penstock was recorded by the Garrison Project Power Plant Control System (PPCS). The combined daily outflows are plotted in Figure 2-11. Hourly reservoir outflow was used during all simulations so that the reservoir temperature model could respond to outflow fluctuations and selective withdrawal created by the plywood trash rack covers.

2.5.3 INFLOW TEMPERATURE

Inflow temperatures for 2003 and 2004 were derived from observations and historic temperature trends used in the Coldwater Habitat Model study published in July 1994.

Actual Missouri River temperatures measured at 15-minute intervals at the USGS stream gage (Williston, ND 06330000) were averaged to daily temperatures for model use. Temperature was available in 2005 and 2006; however, temperatures in 2007 were available only during part of the year because of equipment problems at the gage site. Inflow temperatures are plotted in Figure 2-12.

Few measurements of temperature in the Little Missouri River at Watford City, ND and no USGS record existed so the same dataset was used for the Little Missouri River although actual temperatures would likely be warmer because of shallower flows.

2.5.4 INFLOW DISSOLVED OXYGEN

Dissolved oxygen measurements were made with samples taken at the inflow locations to the reservoir; however, since a continuous record of DO was needed at the modeled reservoir inlet, it was approximated as the saturated DO concentration using an empirical equation. The equation provided by the Environmental Laboratory of ERDC approximates DO concentrations in milligrams per liter of water (mg/L) as a function of water temperature (*T*) in Kelvin (K) and elevation (*z*) in kilometers (km). Measured and assumed water temperatures were used in the approximation, and the resulting DO concentrations are shown in Figure 2-13. Computed DO concentrations were within 5.0 to 10.0 percent of measured DO concentrations.

$$DO = (1 - 0.1148z)\exp\left(-139.3441 + \frac{1.58x10^{5}}{T} - \frac{6.64x10^{7}}{T^{2}} + \frac{1.24x10^{10}}{T^{3}} - \frac{8.62x10^{11}}{T^{4}}\right)$$

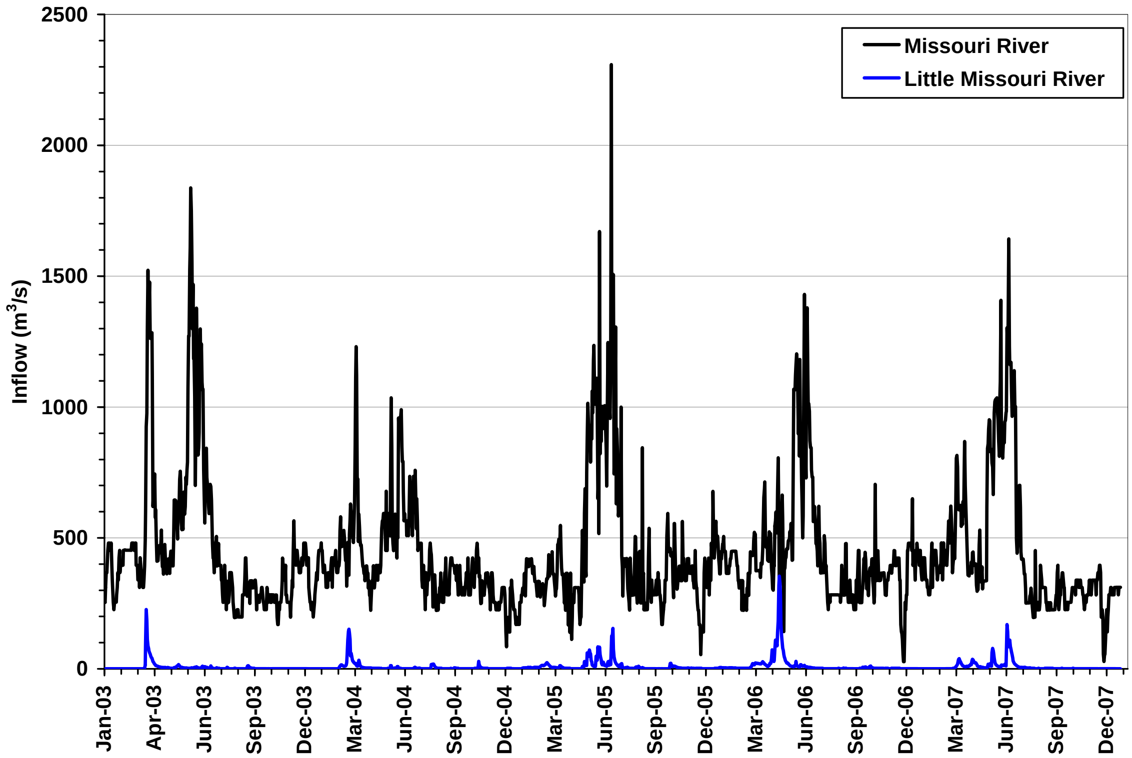


Figure 2-10. Missouri River and Little Missouri River inflows to Lake Sakakawea.

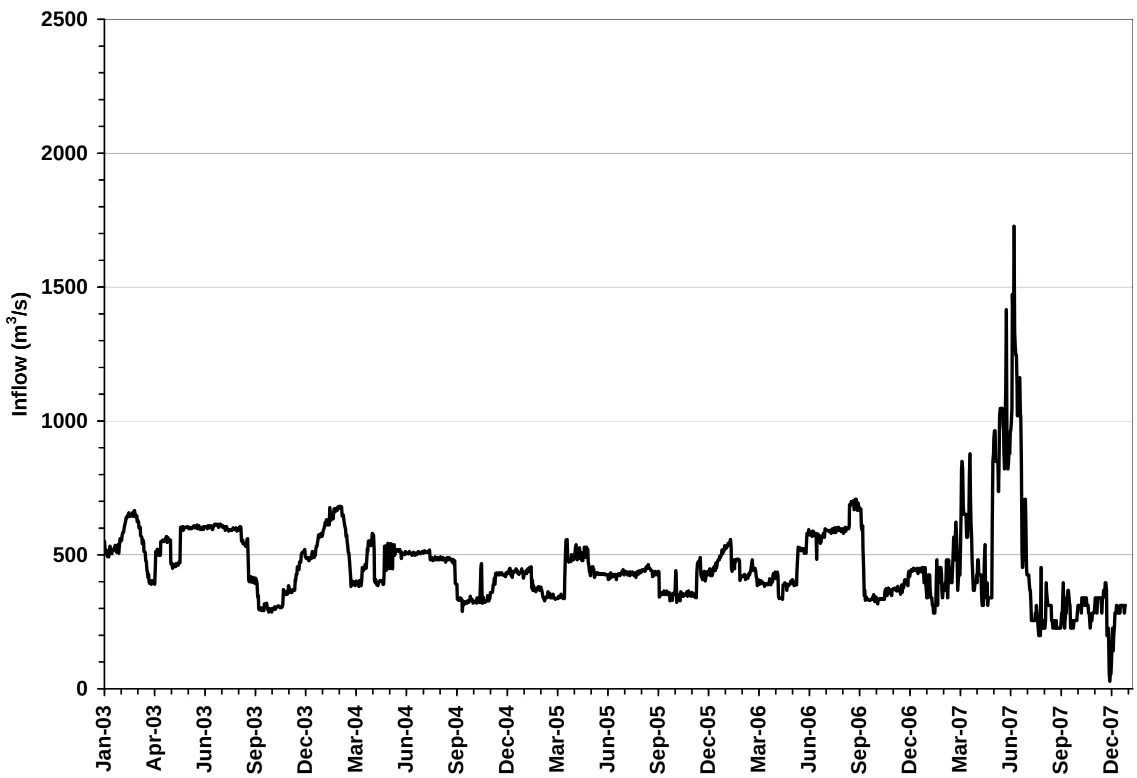


Figure 2-11. Garrison Dam average daily discharge.

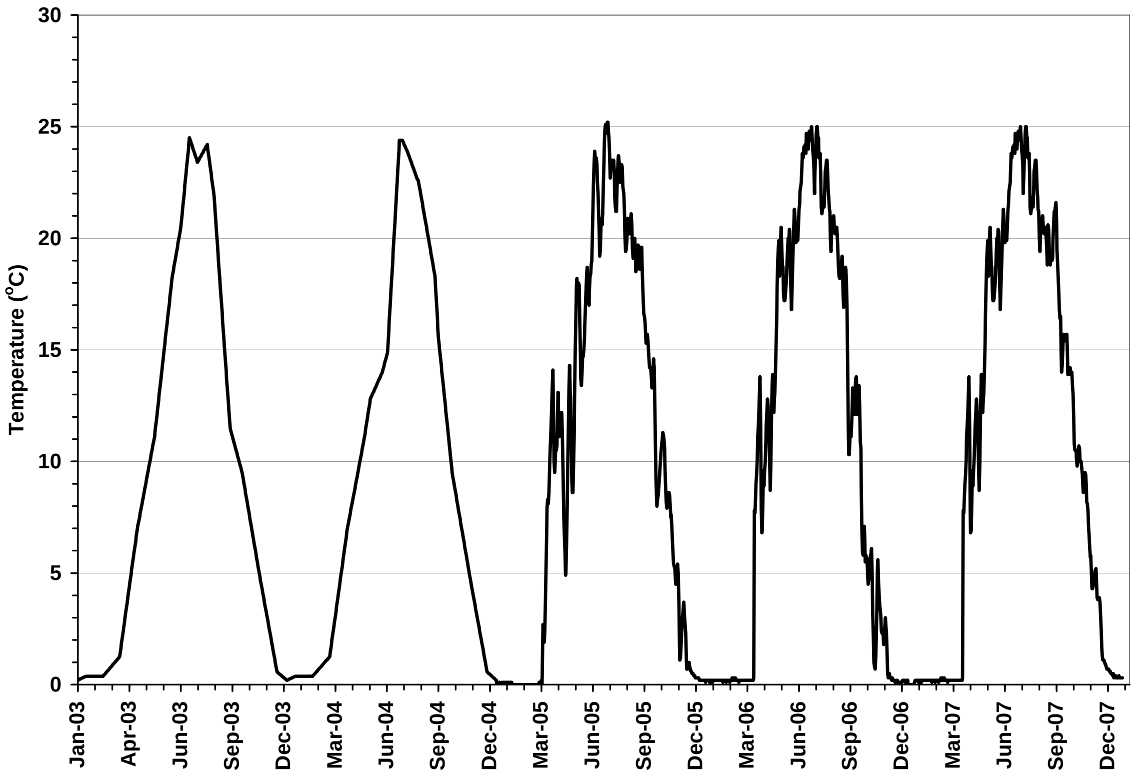


Figure 2-12. Missouri River and Little Missouri River inflow temperature.

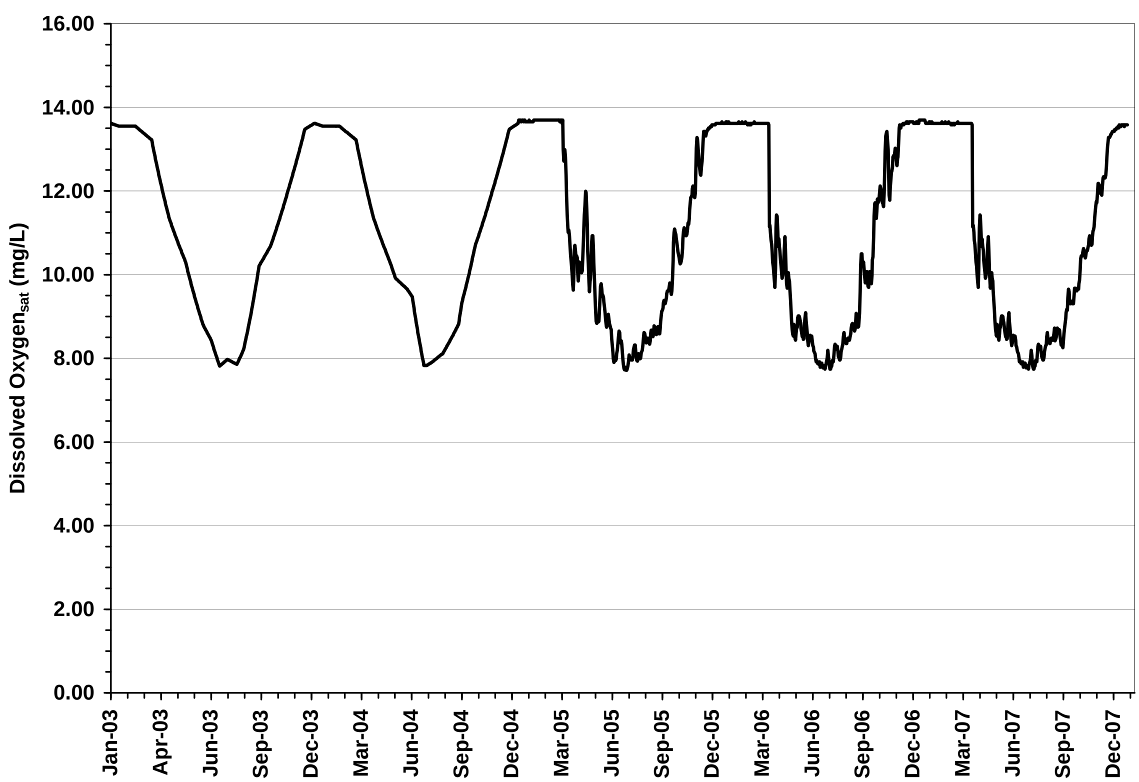


Figure 2-13. Dissolved oxygen saturation concentration in the Missouri River and Little Missouri River.

2.5.5 INFLOW CONSTITUENT CONCENTRATIONS

Water quality samples were taken during the survey period at two inflow locations: 1) GARNFMORR1 on the Missouri River near Williston, ND, and 2) GARNFLMOR1 on the Little Missouri River at North Dakota State Highway 22 north of Kildeer, ND. Water samples were taken at a frequency of about four to six times per year and analyzed for a number of water quality constituents including: suspended solids, alkalinity, total ammonia, dissolved solids, dissolved and total iron, dissolved and total manganese, nitrate/nitrate, total and ortho-phosphorus, total and dissolved silica, sulfate, total Kjeldahl nitrogen, and total and dissolved organic carbon. In addition water temperature, DO, pH, specific conductance, turbidity and sometimes chlorophyll *a* were measured in the field. From the measured constituent concentrations the following constituents' concentrations were input into the model: total dissolved solids, suspended solids, phosphate phosphorus, ammonium, nitrate/nitrite, dissolved silica, particulate silica, total iron, labile and refractory dissolved organic matter, labile and refractory particulate organic matter, algae, DO, and alkalinity.

Dissolved and particulate organic matter was estimated from total organic carbon concentrations at an organic carbon to organic matter ratio of 0.45. Furthermore through model calibration, 90 percent of organic matter was assumed dissolved and 10 percent was assumed particulate, and 10 percent of organic matter was assumed labile and 90 percent was assumed refractory.

Since a continuous daily inflow constituent record was not possible, constituent concentrations were assumed at the beginning of each month in each simulation year along with the actual concentrations on the sampling dates. In the absence of sampled constituent concentrations at the Little Missouri River location, Missouri River concentrations were used. Since inflows from the Little Missouri River are a very small percentage of total inflows, Little Missouri River inflow concentrations have very limited influence on constituent concentrations

3 WATER TEMPERATURE & CONSTITUENT CALIBRATION

Reservoir hydrodynamics were calibrated by running a water balance routine to match the simulated reservoir inflow-outflow-storage to the observed inflow-outflow-storage. Reservoir temperatures and dissolved oxygen were calibrated at three locations where temperature profiles were measured throughout the observing years. In addition powerhouse release temperatures and dissolved oxygen concentrations were compared to observations as an additional level of model calibration.

3.1 OBSERVED WATER QUALITY DATA

Locations where temperature measurements were taken are shown in Figure 1-1. Temperature profiles and water quality samples for laboratory analysis were taken only on designated sampling dates that took place one to two times per month from May to October. Garrison Dam release temperatures were measured in the raw water loop in 2003 and in each of five penstocks from 2004 through 2007 with Hydrolabs from May through October. For calibration purposes, hourly release temperatures were used.

Table 3-1. Sample points, CEQUAL-W2 segment numbers, and approximate lake kilometer.

Site Name	Alternate Name	Model Segment Number	Distance from Dam (km)
GARLK1390A	IP1	54	5
GARLK1399DW	IP2	52	15
GARLK1412DW	IP3	48	35
GARLK1428DW	IP4	41	65
GARLK1445DW	IP5	37	90
GARLK1454DW	IP6	34	105
GARLK1481DW	IP7	25	150
GARLK1493DW	IP8	21	170

3.1.1 TEMPERATURE

Depth-discrete lake temperatures were measured in the field at one-meter depth increments with Hydrolab instruments at eight different locations along the old Missouri River channel in Lake Sakakawea. Temperature profiles were constructed from the measurements for comparison to simulated CE-QUAL-W2 temperatures. In 2006, temperature measurements were made at locations IP1, IP2, IP3, IP5, and IP7; while in 2007 measurements were made at locations IP1, IP3, IP5, and IP7.

Dam release temperature through the Garrison powerhouse was monitored on an hourly basis with Hydrolab instruments in water drawn from the raw water loop through July 2005. After July 2005, temperature was measured on a continuous basis in water drawn from each individual penstock.

3.1.2 WATER QUALITY

Water quality samples were collected from the eight in-pool locations at near-surface, mid-metalimnion, and near bottom water column depths. Near surface samples were collected with a plastic churn bucket, while mid-metalimnion and near bottom samples were collected with a Kemmerer sampler. A list of water quality constituents analyzed for by the Corps' Environmental Chemistry Branch Laboratory is provided in Table 3.3 of the Water Quality Special Study Report for the Garrison Project (USACE, 2006).

Dissolved oxygen was measured directly with Hydrolab instruments simultaneously with lake temperature and dam release temperature measurements. Dissolved oxygen was the primary water quality constituent used in the calibration process, and dissolved solids was used to a limited degree.

3.2 RESERVOIR ELEVATION

The water balance routine computes the difference in observed reservoir storage and simulated reservoir storage by feeding the program observed and simulated pool elevations, then computing reservoir inflow or outflow needed to balance the storage. The hydrodynamic calibration is completed when the water balance inflows and outflows are added back to the reservoir in a subsequent simulation to attain a balanced pool. The resulting pool elevations are shown in Figure 3-1.

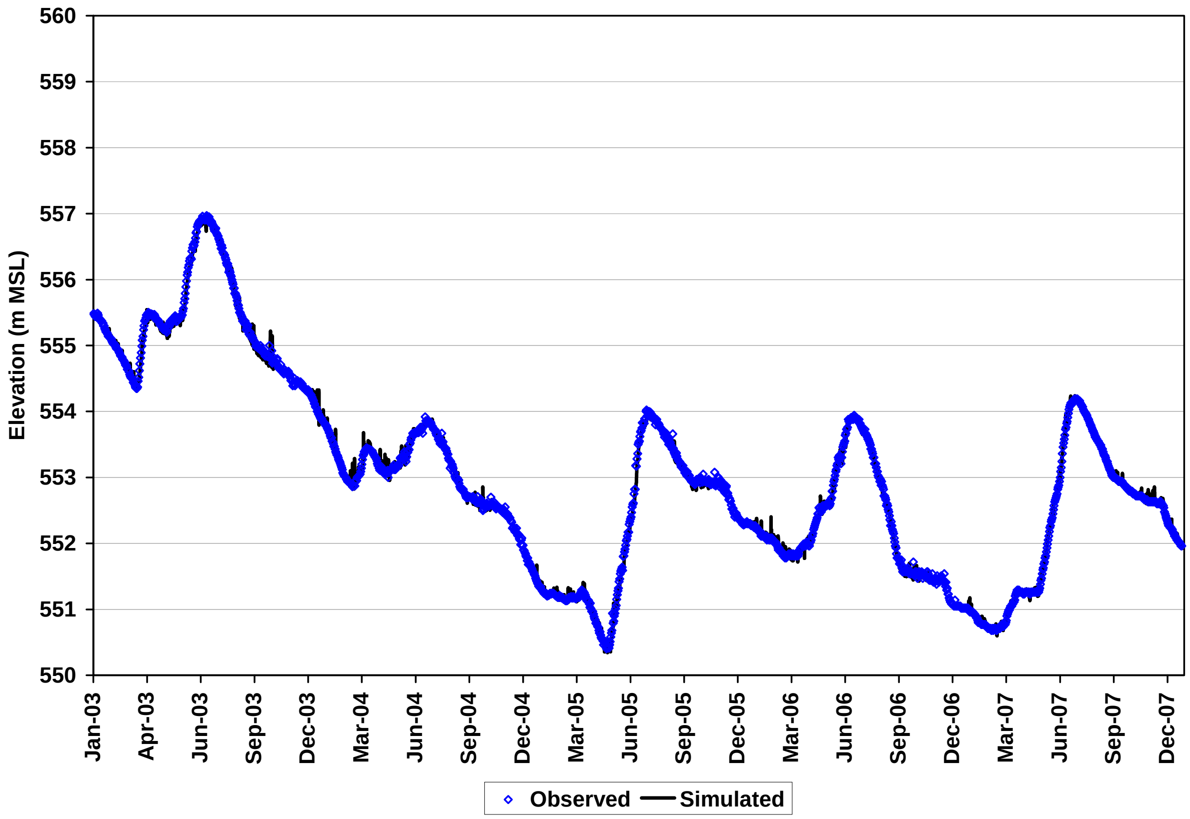


Figure 3-1. Observed and simulated Lake Sakakawea pool elevation for 2003 through 2007.

3.3 RESERVOIR TEMPERATURES

Simulated reservoir temperatures were calibrated to temperature profiles measured at locations IP1 through IP7 in 2003, 2004, and 2005; and, at locations IP1, IP3, IP5, and IP7 in 2006 and 2007. For consistency, only calibrations at IP1, IP3, and IP5 are presented in this report.

Factors that affected temperature calibrations the most included wind sheltering coefficients (WSC) and shortwave solar radiation. In all simulations WSC's were generally set at 1.0, however 2007 WSC's were raised to 1.1 through the middle of the 2007 calibration year because the pool required more vertical mixing to achieve a temperature profile similar to the observed temperature profiles. In addition, shortwave solar radiation was increased to 95 percent of total radiation in order to raise overall temperatures slightly, while shortwave solar radiation in all other simulations remained at 90 percent of total solar radiation.

Statistically the best temperature calibrations were achieved in 2004 and 2006 while 2005 and 2007 were the least accurate (Table 3-2). Absolute errors ranged from 0.61 to 0.86 degrees C with an average of 0.74 degrees C, while root-mean-square (RMS) errors ranged from 0.80 to 1.20 degrees C with an average of 0.92 degrees C (Table 3-2). Plots showing simulated versus observed temperature profiles at lake locations IP1, IP3 and IP5 are provided in the supplemental Figures 9-1 to 9-15 at the end of the report.

Table 3-2. Average annual absolute and root mean square errors between measured and simulated reservoir temperatures and dissolved oxygen concentrations over three reservoir locations (IP1, IP3, & IP5).

Year	Temperature (^{o}C)		Dissolved Oxygen (mg/L)	
	Absolute	Root-Mean Square	Absolute	Root-Mean Square
2003	0.72	0.98	0.59	0.78
2004	0.61	0.79	0.60	0.75
2005	0.86	1.20	0.61	0.86
2006	0.69	0.82	0.64	0.80
2007	0.81	0.80	0.50	0.61
Average	0.74	0.92	0.59	0.76

3.4 RESERVOIR DISSOLVED OXYGEN

Factors that affected DO calibrations the most included initial reservoir concentrations of labile dissolved and particulate organic matter and inflow concentrations of labile dissolved and particulate organic matter. Labile and refractory percentages of total organic matter are described in the previous section 2.5.5 of this report. Additionally, inflow water concentrations containing 10 percent of the organic matter in the particulate phase was essential to simulating observed DO concentrations.

Statistically the best DO calibration with the lowest absolute and RMS errors was achieved in 2007 while 2005 and 2006 were the least accurate calibrations based on computed errors (Table 3-2). The average absolute and RMS errors were 0.59 mg/L and 0.76 mg/L, respectively. Plots showing simulated versus observed DO profiles at lake locations IP1, IP3 and IP5 are provided in the supplemental Figures 9-16 to 9-30 at the end of the report.

3.5 RESERVOIR OUTFLOW

Hydrolabs were installed in the powerhouse to record temperature and DO concentrations of power releases through the raw water loop, and after July 2005 in each of the five penstocks. The CE-QUAL-W2 model produces simulated output for combined powerhouse releases, temperatures, and constituent concentrations, yet it does not produce individual penstock outputs. The simulated and observed flow-weighted temperatures and dissolved oxygen concentrations are compared as an additional means of calibration.

3.5.1 OUTFLOW TEMPERATURES

Combined simulated outflow temperatures on a six-hour time step are plotted against hourly observed flow-weighted temperatures in Figure 3-2. Absolute and root-mean square errors between observed and simulated outflow temperatures are provided in Table 3-3. In general the model produced close-fitting release temperatures when compared to observed temperatures; however, it was unable to produce the variability in release temperatures that was exhibited in temperatures recorded in the raw-water loop and penstocks. The two-dimensional, lateral averaging computational method employed by the model is the main reason that simulated outlet temperatures lack the variability exhibited in observed outlet temperatures.

Table 3-3. Average annual absolute and root mean square errors between measured and simulated outflow temperatures and dissolved oxygen concentrations.

Year	Temperature (^{o}C)		Dissolved Oxygen (mg/L)	
	Absolute	Root-Mean Square	Absolute	Root-Mean Square
2003	1.47	2.03	0.51	0.89
2004	0.89	1.26	1.13	1.39
2005	0.74	0.97	0.80	0.97
2006	0.84	1.16	0.41	0.50
2007	1.28	1.60	0.73	0.96
Average	0.96	1.34	0.78	1.04

3.5.2 OUTFLOW DISSOLVED OXYGEN

Combined simulated outflow DO concentrations are plotted against hourly observed flow-weighted DO in Figure 3-3. Absolute and root-mean square errors between observed and simulated outflow dissolved oxygen concentrations are provided in Table 3-3. While the 2003 simulation produced a close fit of DO, the 2004 and 2005 simulations were not able to reproduce the variability in observed DO concentrations. In the observed data it was noted that the Hydrolabs were not calibrated correctly, which may explain shifts in the observed DO concentrations especially in 2004. In addition, simulated DO concentrations appeared to be about 0.5 mg/L above observed concentrations.

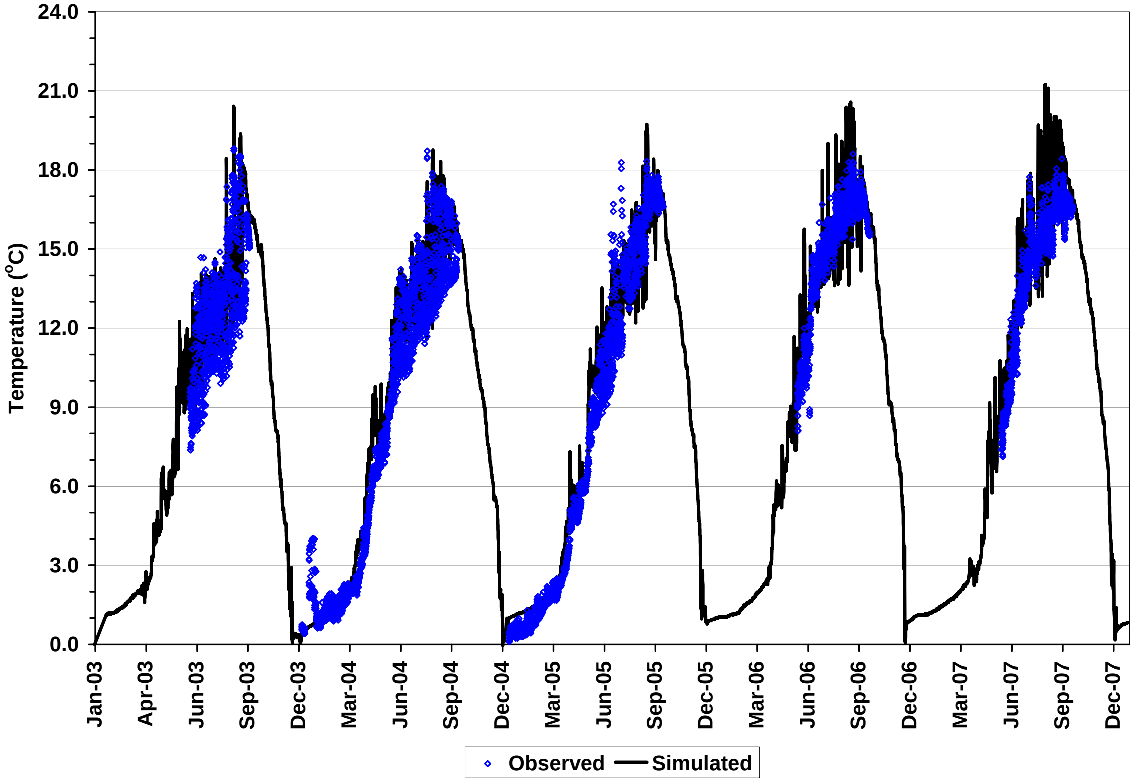


Figure 3-2. Simulated and observed Garrison powerhouse release temperatures.

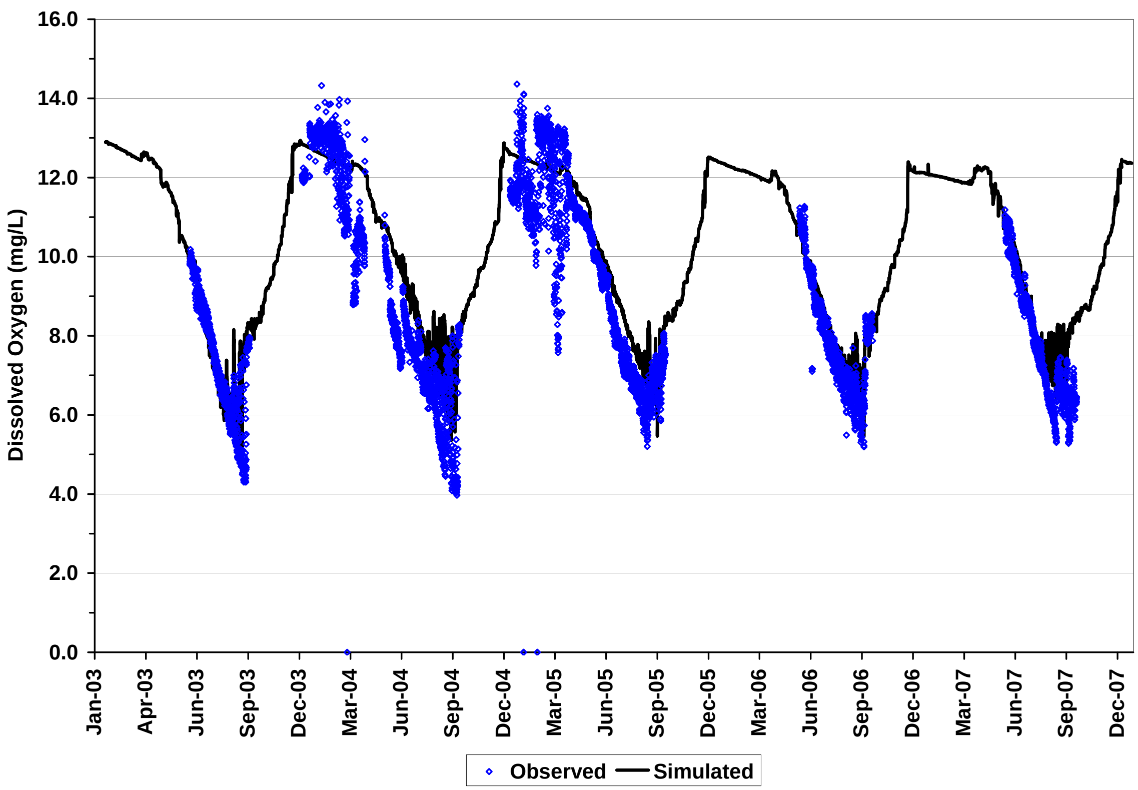


Figure 3-3. Simulated and observed Garrison powerhouse dissolved oxygen concentrations.

4 WATER QUALITY ASSESSMENT UNDER EXISTING CONDITIONS

Water quality was assessed based on reservoir temperatures and dissolved oxygen concentrations with respect to CWH criteria. Existing condition simulations were performed from 2003 to 2007 using the calibrated temperature and water quality model. Simulations incorporated trash rack barriers in 2005 and 2006 at Intake Towers 2 and 3, and in 2007 at Intake Towers 1, 2, and 3. To aid the interpretation of the temperature and dissolved oxygen plots, pool elevations are shown in Figure 4-1.

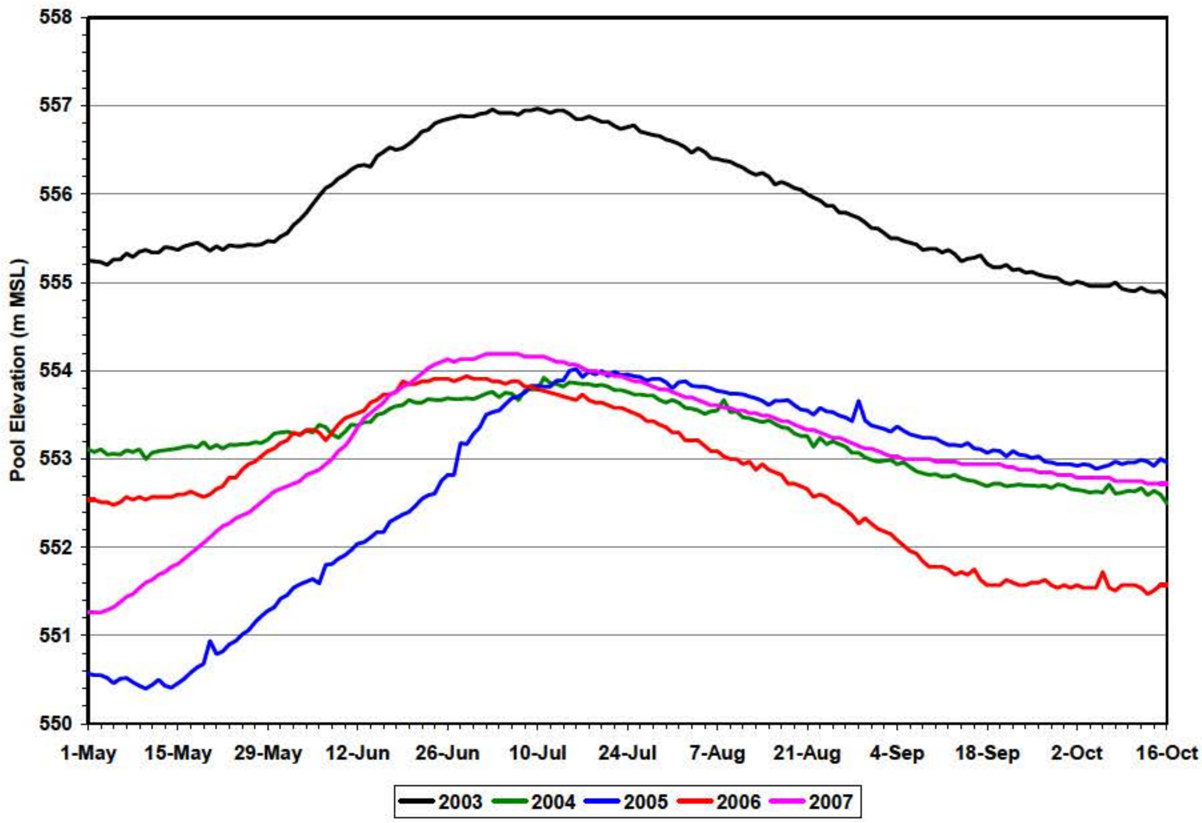


Figure 4-1. Simulated daily pool elevation of the existing Lake Sakakawea reservoir operating conditions from May 1 to October 16.

4.1 TEMPERATURE TRENDS

The presence of water that meets the maximum CWH temperature requirement of 15 degrees C is the greatest temperature water quality concern in Lake Sakakawea. The simulated temperature time series at the intake tunnel centerline elevation of 513.6 m (1685.0 ft) is plotted from May 1 to October 16 in 2003 through 2007 in Figure 4-2. These time series represent the temperature of water that persists near the normal inlet elevation and is an indication of CWH that meets the 15 degrees C criterion.

Simulation year 2003 exhibits the lowest inlet temperatures while 2004 and 2005 were higher by about 2 degrees C from early June to early August, and 2006 and 2007 were higher by about 1.5 degrees C. Greater reservoir volume indicated by higher pool elevations of 1.8 to 3.0 m (6.0 to 10.0 ft) probably contributed to lower intake tunnel bottom temperatures in 2003. The impact of trash rack barriers and their bottom withdrawal limitations is not readily evident in the intake tunnel elevation temperatures.

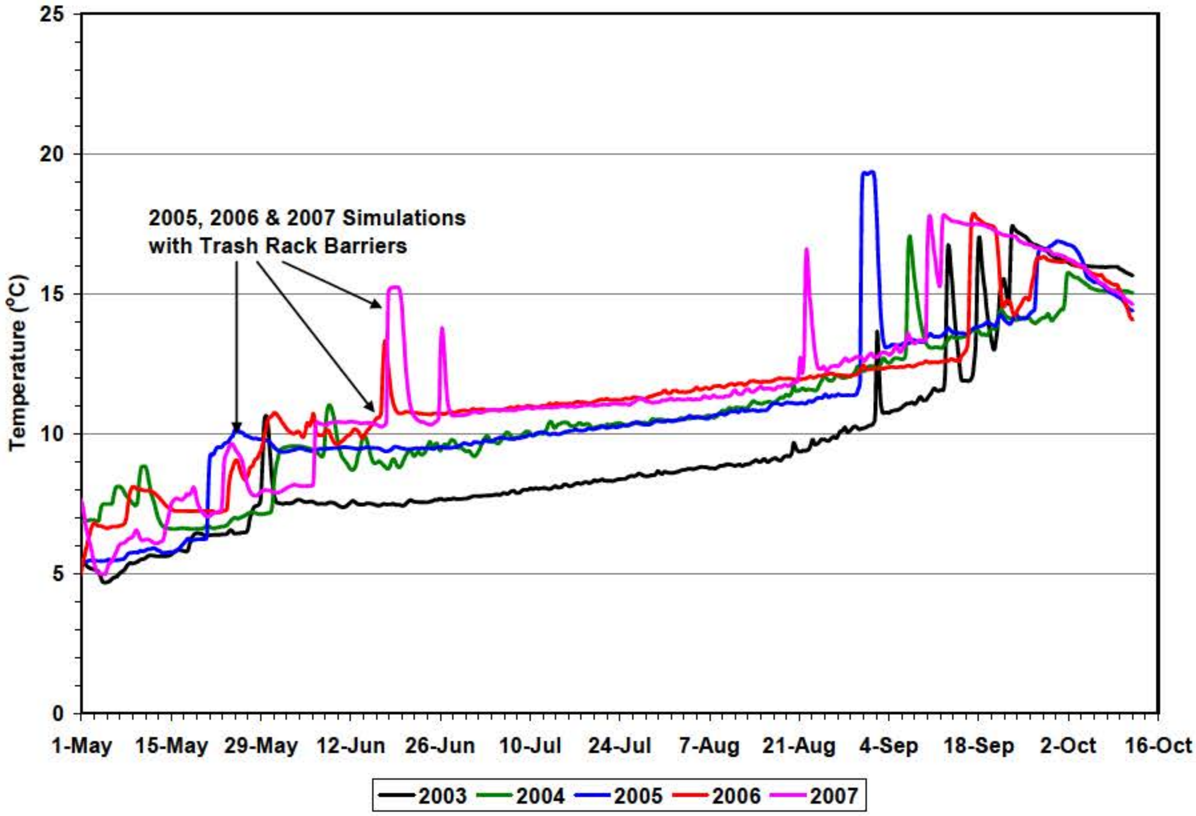


Figure 4-2. Simulated water temperatures near the intake tunnel centerline elevation 513.6 m (1685.0 ft) at site L1 – Government Bay, from May 1 to October 16.

Temperatures near the intake tunnel elevation rarely exceeded 15 degrees C until August and September in all years when stratification began breaking down due to bottom withdrawals and low reservoir volumes. All temperatures exceeded 15 degrees C at the time of reservoir turnover which commenced in the month of September. The latest simulated turnover occurred on October 2, 2004, which was the coldest year of simulation and the earliest occurred on September 11, 2007.

4.2 DISSOLVED OXYGEN TRENDS

Water must meet the minimum 5 mg/L dissolved oxygen (DO) concentration in order to meet the CWH DO criteria in Lake Sakakawea. The DO concentration time series at the intake tunnel centerline elevation of 513.6 m (1685.0 ft) is plotted from May 1 to October 16 in 2003 through 2007 in Figure 4-3. These time series represent the DO concentration of water that persists near the normal inlet elevation and is an indication of CWH that meets the 5 mg/L criterion.

Simulation year 2003 exhibits slightly higher DO concentrations through early August while other simulations years are 1.0 to 1.5 mg/L lower than 2003. The impact of trash rack barriers and their bottom withdrawal limitations is not readily evident in the intake tunnel DO concentrations; however, DO concentrations fell below 5 mg/L at earlier dates during 2006 and 2007, the years that the barriers were at their fullest implementation. Bottom reservoir withdrawals aid hypolimnetic mixing and aeration; therefore, mixing and aeration was limited in the hypolimnion with the implementation of the trash rack barriers. At the time of reservoir turnover and re-aeration in all simulations, DO concentrations rose above 5 mg/L and were restored to about 8 mg/L near the intake tunnel elevation.

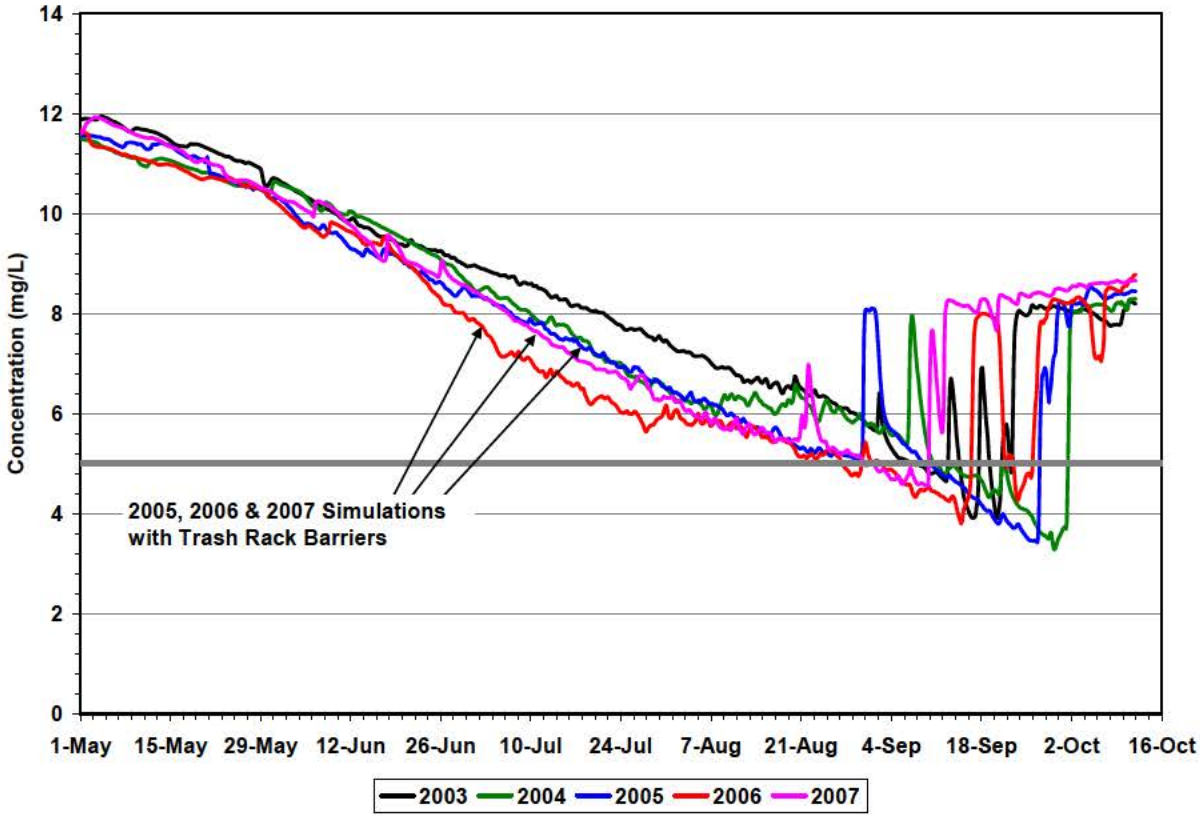


Figure 4-3. Simulated dissolved oxygen concentrations near the intake tunnel centerline elevation 513.6 m (1685.0 ft) at site L1 – Government Bay, from May 1 to October 16.

4.3 COLDWATER HABITAT

Coldwater habitat (CWH) is defined as water in the reservoir that meets the minimum DO concentration of 5 mg/L and maximum temperature of 15 to 18.3 degrees C, and is therefore suitable habitat for certain species of fish. Optimal CWH meets the minimum DO concentration requirement and the more stringent maximum temperature of 15 degrees C, while total CWH must meet the maximum temperature of 18.3 degrees C. CWH was estimated in Lake Sakakawea based on measured water temperature and dissolved oxygen depth profiles applied to zone volumes for each measurement location.

The calibrated CE-QUAL-W2 model was used to estimate CWH by summing the volume of water that met both the optimal and total CWH temperature and DO criteria. CWH is expressed in units of million acre feet (MAF) in this report because acre-feet is the conventional unit for reporting reservoir storage volume.

4.3.1 ELEVATION OF COLDWATER HABITAT CRITERIA

The simulated elevations of constant temperature and DO concentration criteria for optimal CWH for the 1st and median day of each month in 2003, 2004, 2005, 2006, and 2007 are plotted in Figure 4-4. Simulations years 2005, 2006, and 2007 incorporated model parameter changes to represent the trash rack intake barriers used in the field. In this plot the 15 degrees C isotherms all progressively decline in elevation during the year as warmer water above the isotherm is driven deeper into the reservoir and colder water below the isotherm is warmed and released through low level withdrawals. At the same time 5 mg/L DO isopleths rise in elevation beginning in early August indicating a decline in DO concentrations especially

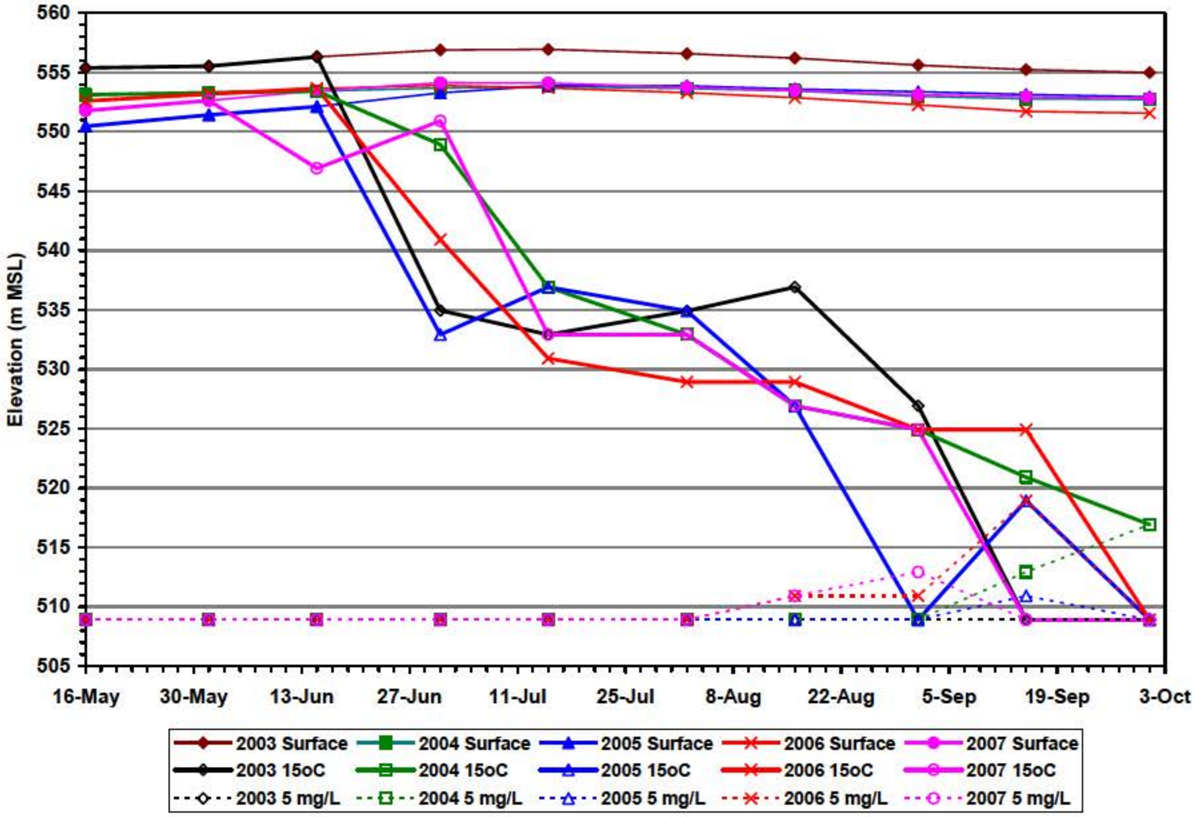


Figure 4-4. Elevation of simulated lake surface, 15°C water temperature, and 5 mg/L dissolved oxygen concentration isopleths by year for station L1 - Government Bay.

near the bottom of the reservoir. The difference in elevation between the isotherms and isopleths represents the thickness of CWH water at location L1.

4.3.2 COLDWATER HABITAT VOLUME

Both marginal and optimal CWH volumes were computed from the 2003 – 2007 simulations using the Animation and Graphics Portfolio Manager (AGPM) for CE-QUAL-W2. Estimated CWH volumes were assumed to be accurate because they were based on direct measurements of temperature and DO concentrations performed during the 2003 through 2007 water quality survey. Computed CWH volumes are plotted against estimated CWH volumes in Figures 4-5 through 4-9.

The fit of simulated CWH versus survey estimated CWH is relatively close in years 2003 and 2004, while in 2005 CWH was not simulated accurately assuming the estimated CWH is an accurate assessment. 2006 optimal CWH fit estimated data very well, while 2007 was less accurate. The model has the potential to accurately simulate CWH during times when temperature and DO measurements are not available or to evaluate the impact of water quality measures used to preserve CWH.

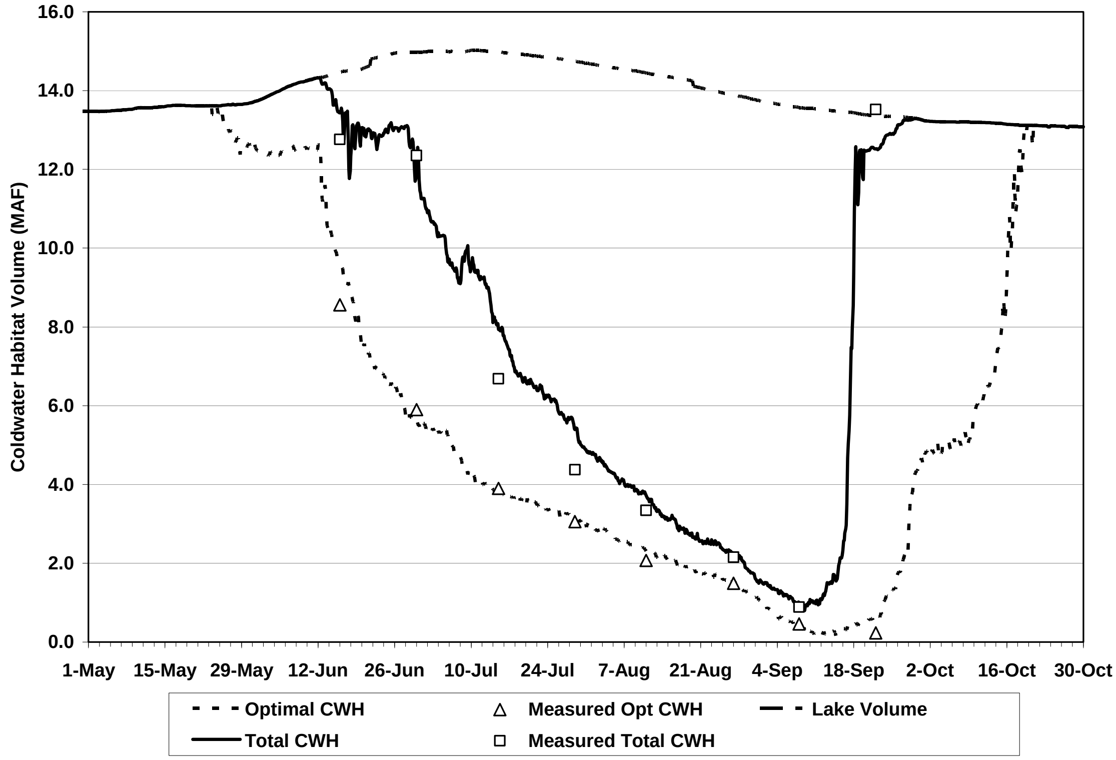


Figure 4-5. Simulated and estimated optimal and total CWH (million acre-feet) in Lake Sakakawea during 2003.

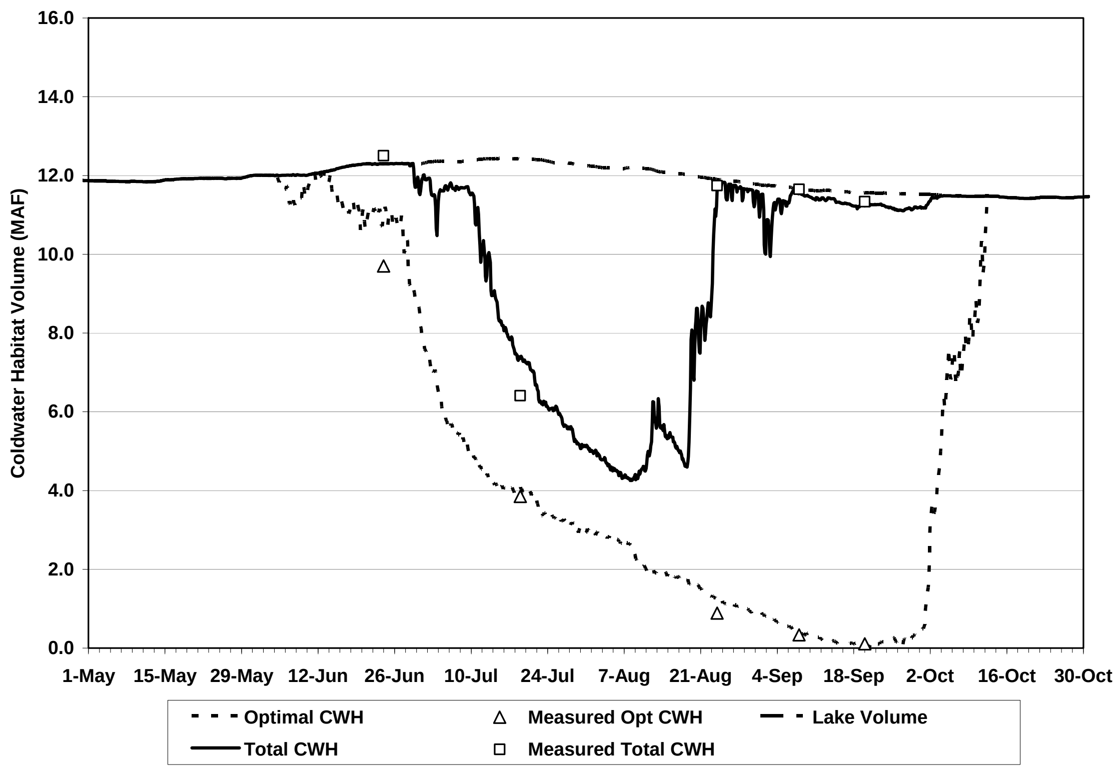


Figure 4-6. Simulated and estimated optimal and total CWH (million acre-feet) in Lake Sakakawea during 2004.

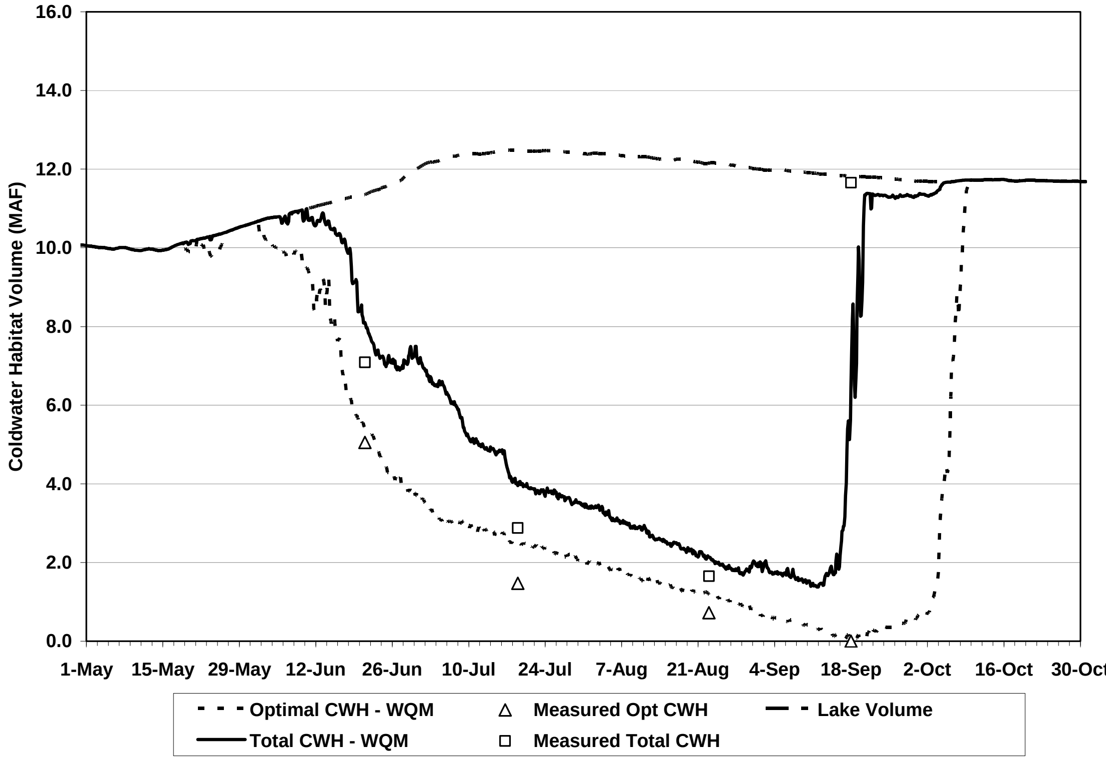


Figure 4-7. Simulated and estimated optimal and total CWH (million acre-feet) in Lake Sakakawea during 2005. Barriers installed on Towers 3 and 2 on July 15 and 20, respectively.

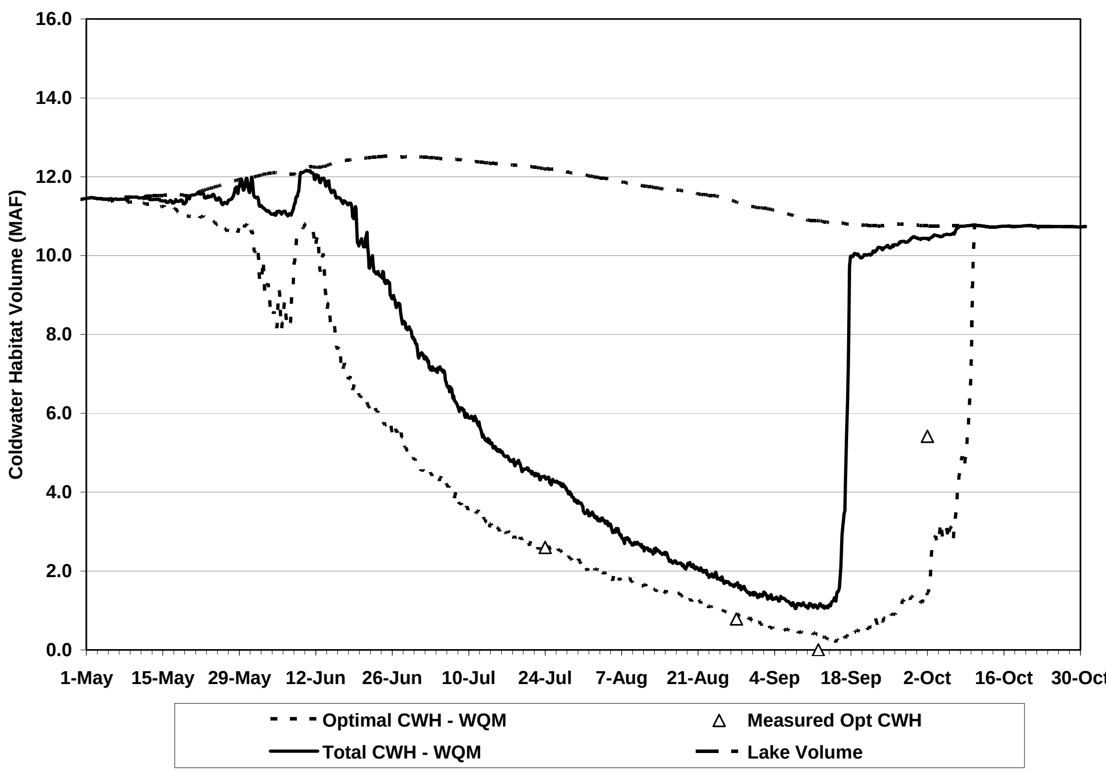


Figure 4-8. Simulated and estimated optimal and total CWH (million acre-feet) in Lake Sakakawea during 2006. Trash rack barriers in place on Towers 2 and 3 all year.

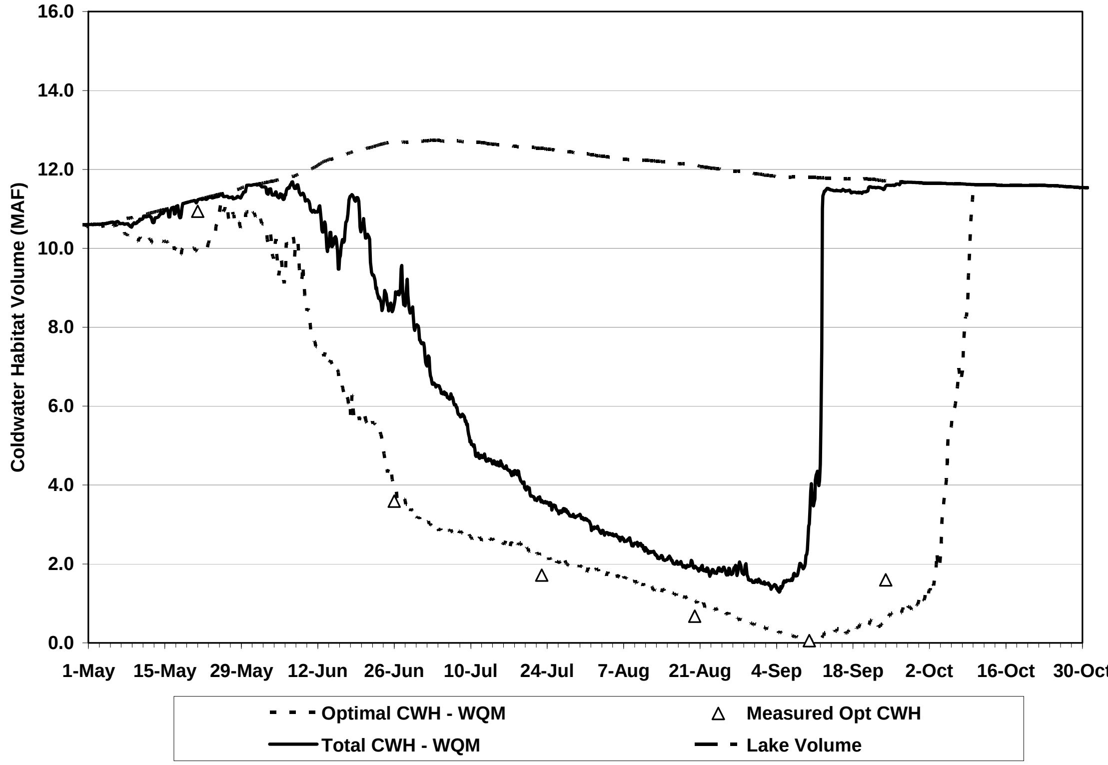


Figure 4-9. Simulated and estimated optimal and total CWH (million acre-feet) in Lake Sakakawea during 2007. Trash rack barriers in place on Towers 2 and 3 all year. Tower 1 installed May 14.

5 ASSESSMENT OF IMPLEMENTED WATER QUALITY MANAGEMENT MEASURES

5.1 INTAKE BARRIER EVALUATION

To evaluate the effectiveness of trash rack intake barrier water quality measures, two sets of simulations were performed: 1) simulations without trash rack intake barriers, and 2) simulations with trash rack intake barriers. Simulations of intake barriers for years 2005, 2006 and 2007 were performed according to the actual level of implementation in the field trials. Barriers were installed on July 15, 2005 on Intake Tower 3 and on July 20, 2005 on Intake Tower 2. Barriers remained in place with the exception of an inspection in 2006. In 2007 barriers were installed on Intake Tower 1 on May 14. Simulations of water quality measures in 2003 and 2004 were performed to the same level of implementation as in the 2007 field trial. Results of water quality simulations were compared to evaluate the differences without and with the intake barriers.

5.1.1 IMPACT OF BARRIERS ON WATER QUALITY

5.1.1.1 Temperature

The impact of trash rack intake barriers on water temperature occurring near the intake tunnel centerline elevation of 513.6 m (1685.0 ft) at water quality site L1 (Government Bay) was evaluated for all simulations years. This location represents the reservoir bottom where CWH should persist throughout the time period of thermal stratification and where bottom withdrawals through the existing intake structure occur. Bottom temperatures in 2006 for simulations without and with intake barriers are plotted in Figure 5-1. Bottom temperatures in 2006 in the simulation with intake barriers (green line) are slightly lower than bottom temperatures without intake barriers (black line).

To evaluate the impact of intake barriers on bottom temperature near the dam, the difference in water temperature between simulations with the implemented trash rack intake barriers and without the implemented trash rack intake barriers was calculated. The temperature differences plotted in Figure 5-2 shows a general decrease in bottom temperature as a result of the intake barriers. Intake barriers lowered temperatures less than 0.5 degrees C through early August. By the end of August bottom temperatures with intake barriers in place were between 0.5 and 1.0 degrees C lower than simulations in which no barriers were implemented. With the exception of 2003 and 2007, most temperature deviations were less than 1.0 degrees C. Five-year average temperature deviations by month were -0.06 degrees C in July, -0.22 degrees C in August, -0.51 degrees C in September, and -0.13 degrees C in October. The statistical significance of the intake barriers at lowering reservoir bottom temperatures near the dam was not tested; however, the general trends show that temperatures were reduced as a result of their implementation. The barriers appeared to preserve colder water in the bottom of the reservoir by: 1) passing warmer water above the intake barriers through the intake towers thus limiting the passage of colder water, and 2) reducing hypolimnetic mixing that occurs as a result of a bottom reservoir withdrawal.

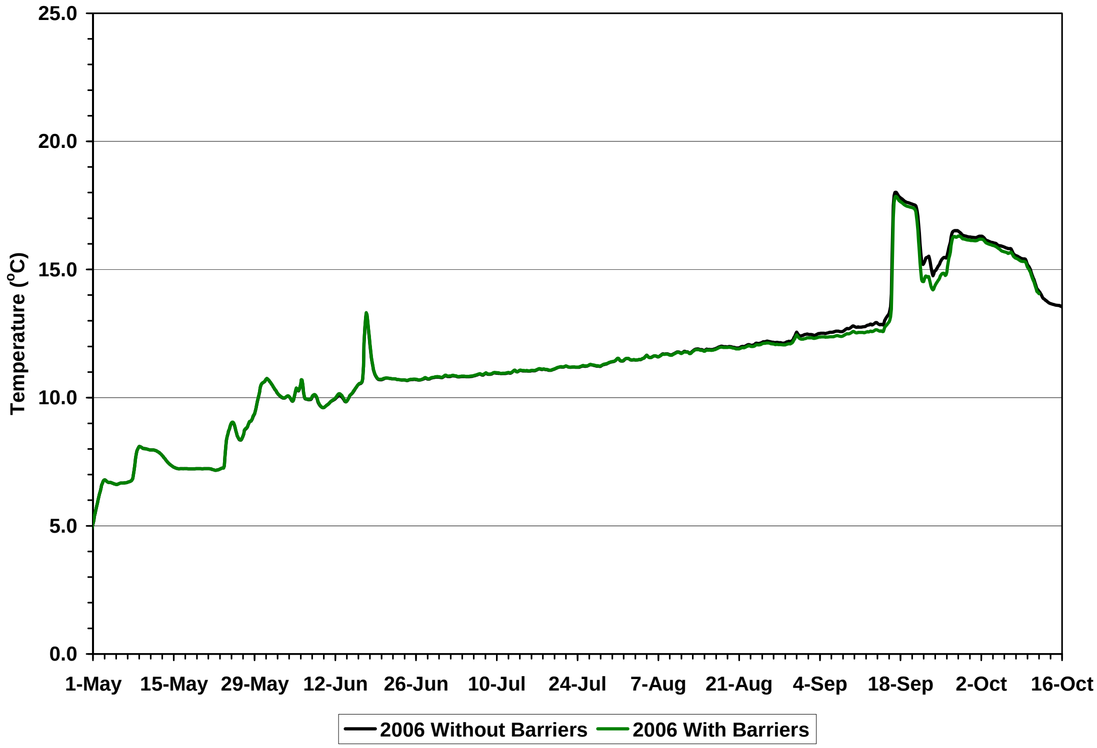


Figure 5-1. 2006 simulated water temperatures near the intake tunnel centerline elevation 513.6 m (1685.0 ft) at site L1 (Government Bay) without and with implemented intake tunnel barriers.

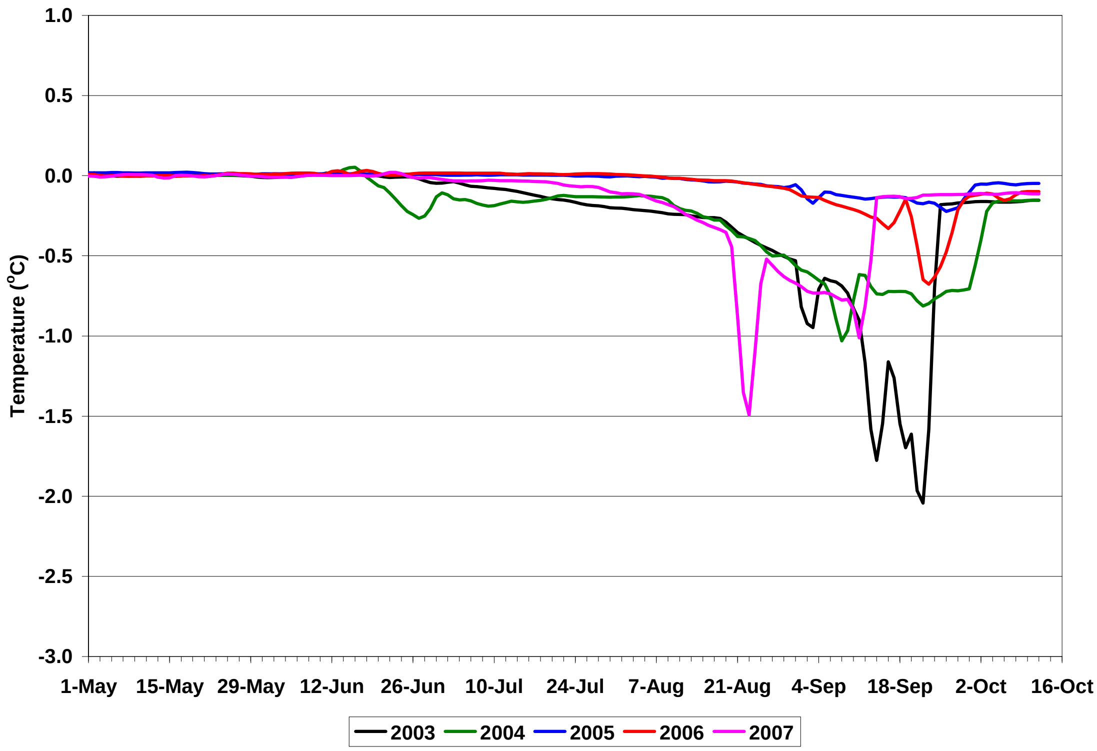


Figure 5-2. Calculated difference between simulated water temperatures near the intake tunnel centerline elevation 513.6 m (1685.0 ft) at site L1 (Government Bay) without and with implemented intake tunnel barriers.

5.1.1.2 **Dissolved Oxygen**

DO concentrations of water occurring near the intake tunnel centerline elevation of 513.6 m (1685.0 ft) at water quality site L1, Government Bay were evaluated for all simulation years and the difference between simulations with the implemented trash rack intake barriers and without the implemented trash rack intake barriers was calculated. The difference in simulated DO concentrations in 2006 (Figure 5-3) indicates the impact of trash rack intake barriers on DO concentrations is marginal.

In September 2006 (Figure 5-3), simulated DO concentrations with the implemented plywood barriers were higher than DO concentrations without the plywood barriers. It is possible that the barriers impede underflows of low DO water along the reservoir bottom resulting in less low DO water being transported through mid-lake regions. The maximum impact would occur during late summer when concentrations of DO in the reservoir bottom were lowest.

Both increases and decreases to DO concentrations occurred as a result of the implemented trash barriers (Figure 5-4). It was expected that DO concentrations may increase slightly since temperatures decreased in the reservoir bottom when intake barriers were implemented; however, this was not always the case. In 2003 and 2007 the barriers appeared to cause an increase in DO and in other years a decrease in DO occurred. Very pronounced decreases occurred in 2005 as a result of the intake barriers, which cannot easily be explained. Low pool elevations occurred early in the year in 2005 and intake barriers were not implemented until July 15 and July 20, yet the barriers appeared to affect no change after implementation. Average DO concentration deviations, excluding 2005 deviations, were 0.00 degrees C in July, 0.03 degrees C in August, 0.10 degrees C in September, and 0.00 degrees C in October. The statistical significance of the impact of intake barriers on DO concentrations was not tested; yet, the simulations do not show an appreciable impact to DO.

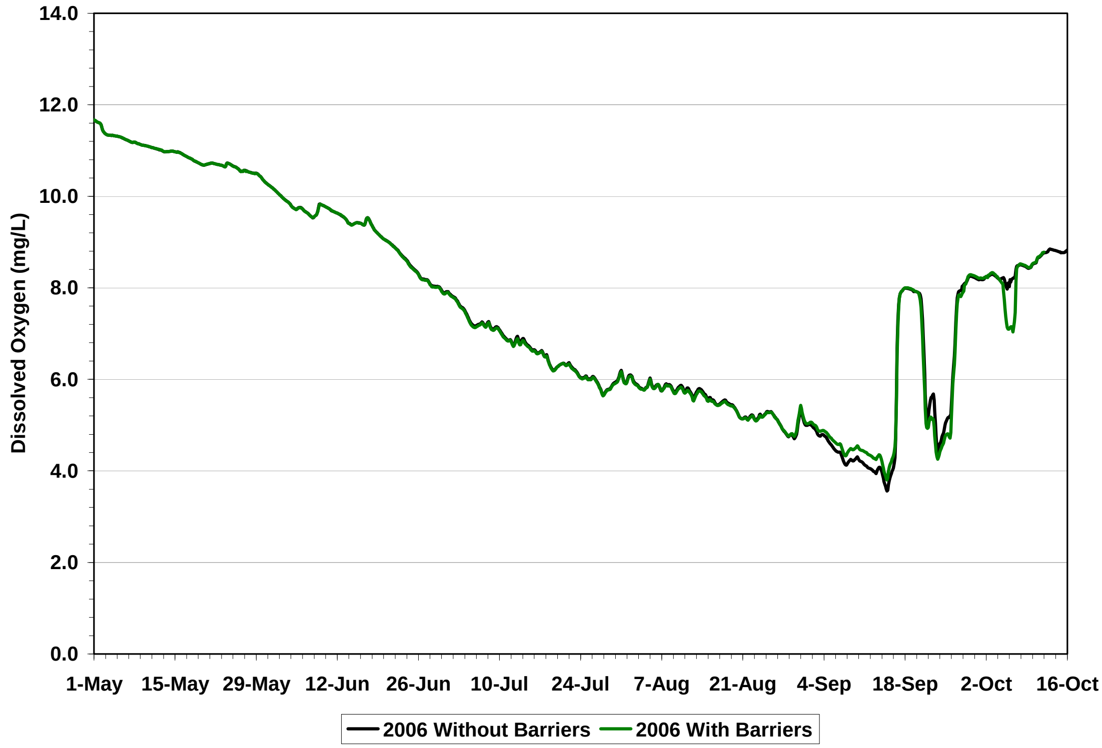


Figure 5-3. 2006 simulated dissolved oxygen concentrations near the intake tunnel centerline elevation 513.6 m (1685.0 ft) at site L1 (Government Bay) without and with implemented intake tunnel barriers.

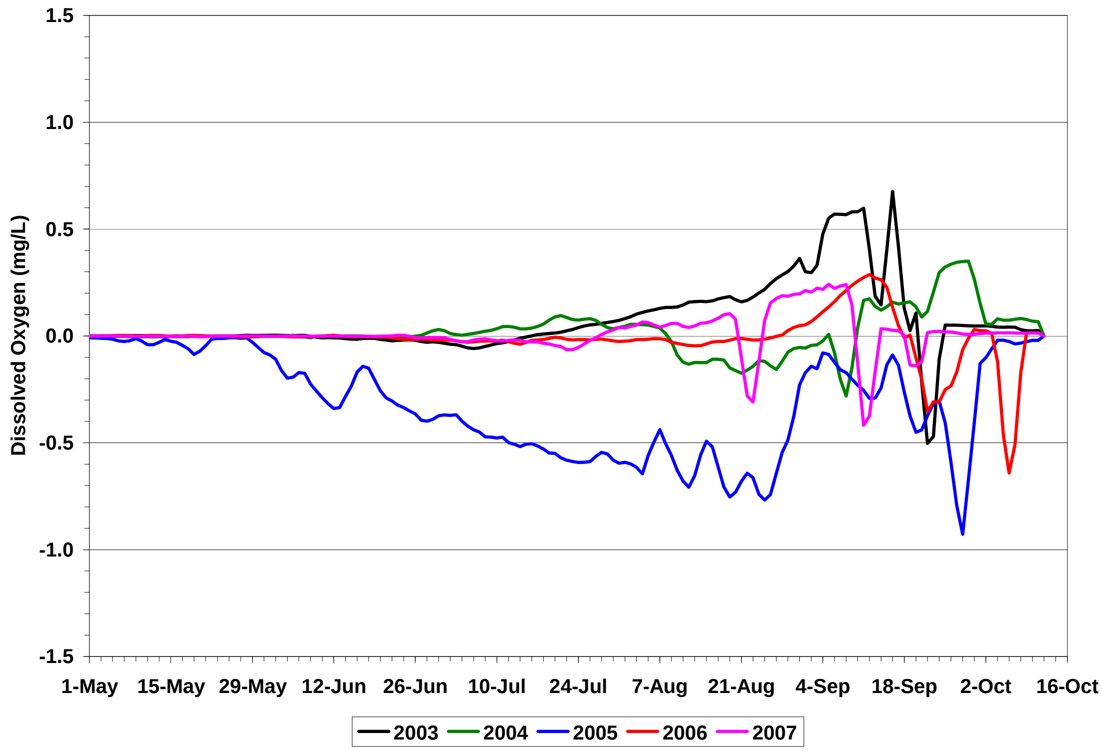


Figure 5-4. Calculated difference between simulated dissolved oxygen concentrations near the intake tunnel centerline elevation 513.6 m (1685.0 ft) at site L1 (Government Bay) without and with implemented intake tunnel barriers.

5.1.2 IMPACT OF BARRIERS ON COLDWATER HABITAT CRITERIA DEPTH

Simulated CWH criteria isotherm (15 degrees C) and DO (5 mg/L) isopleths elevations are plotted versus time for the without and with intake barrier scenarios in Figures 5-5 through 5-9. Since the model is divided into 2-meter vertical layers and laterally averaged, simulation precision is limited, which also limits the simulated differences between without and with intake scenarios elevations. In all simulations intake barriers delayed the elevation decline of the 15 degrees C isotherm; however, the impact of the barriers on 5 mg/L DO isopleths was less evident. Only in the 2004 and 2005 with-intake barrier (WQM) simulations did the 5 mg/L isopleths remain deeper in the water column than the without case as a result of reduced depletion of DO from biomass degradation.

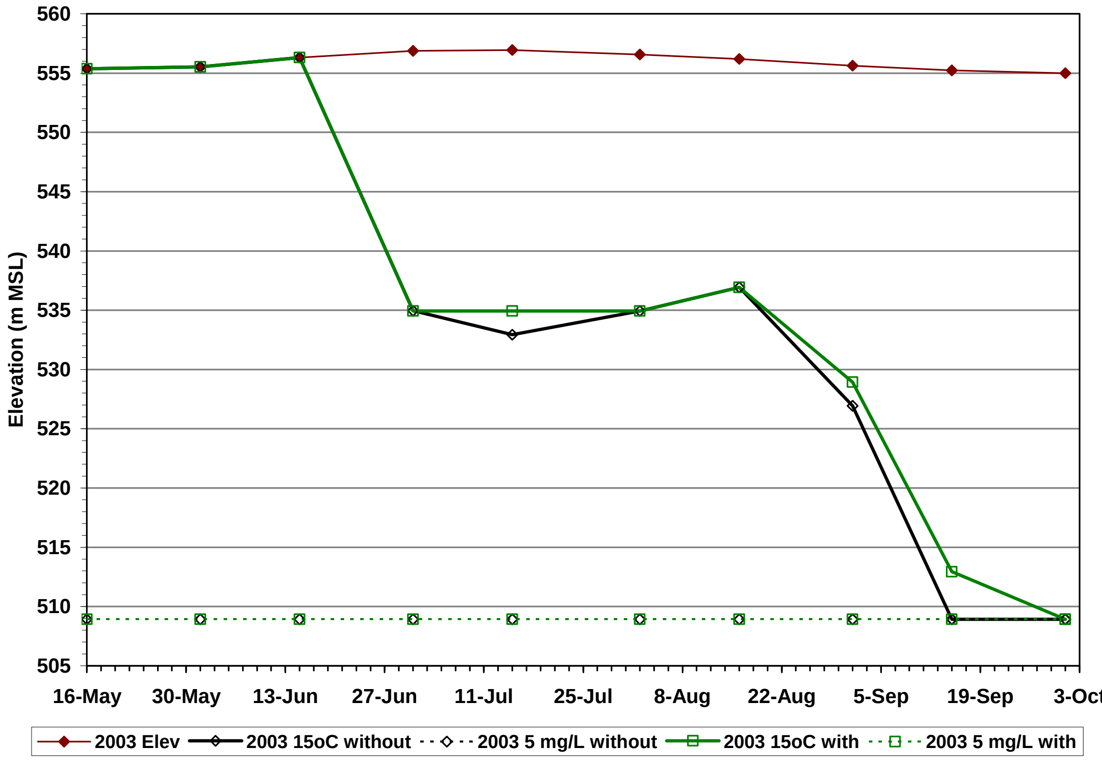


Figure 5-5. Elevation of simulated lake surface, 15°C temperature, and 5 mg/L dissolved oxygen isopleth during 2003 at station L1 - Government Bay with (green) and without (black) trash rack barriers.

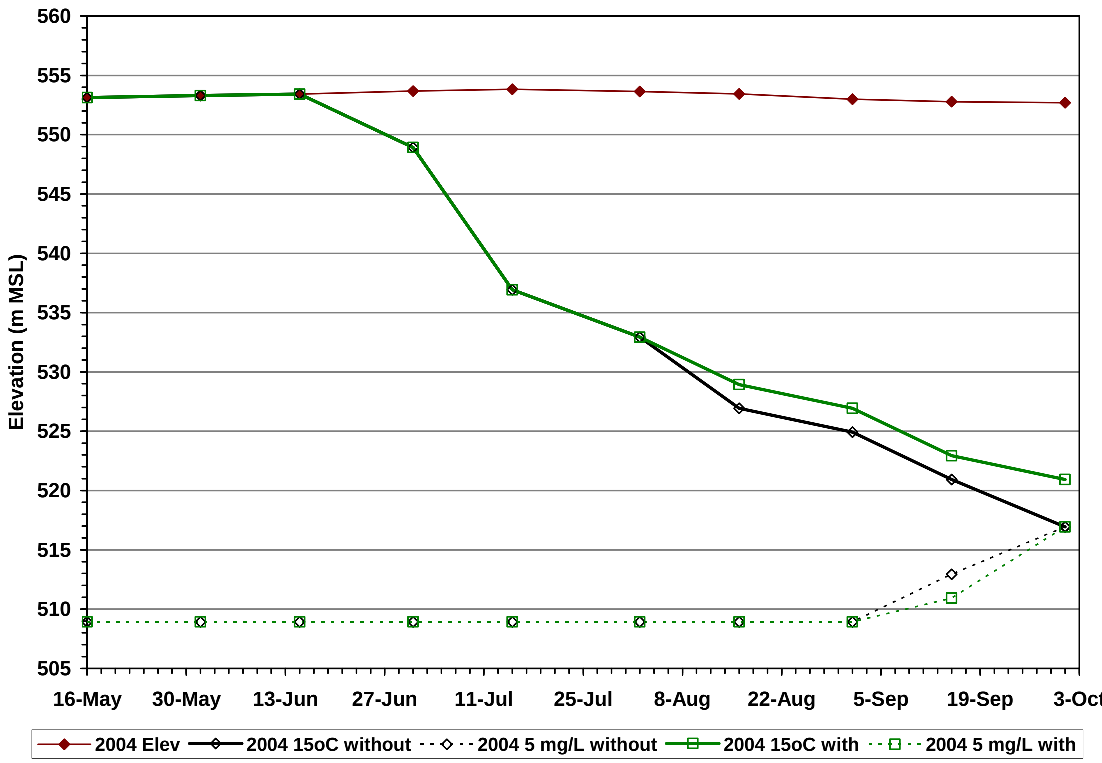


Figure 5-6. Elevation of simulated lake surface, 15°C temperature, and 5 mg/L dissolved oxygen isopleth during 2004 at station L1 - Government Bay with (green) and without (black) trash rack barriers.

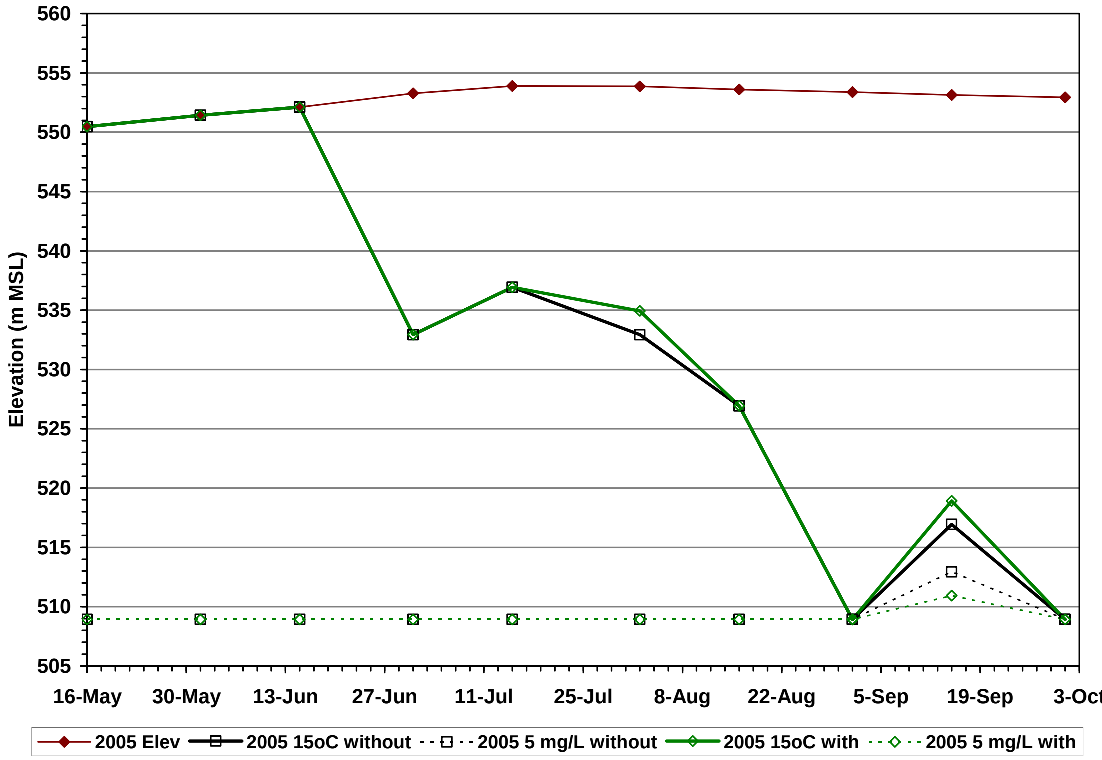


Figure 5-7. Elevation of simulated lake surface, 15°C temperature, and 5 mg/L dissolved oxygen isopleth during 2005 at station L1 - Government Bay with (green) and without (black) trash rack barriers.

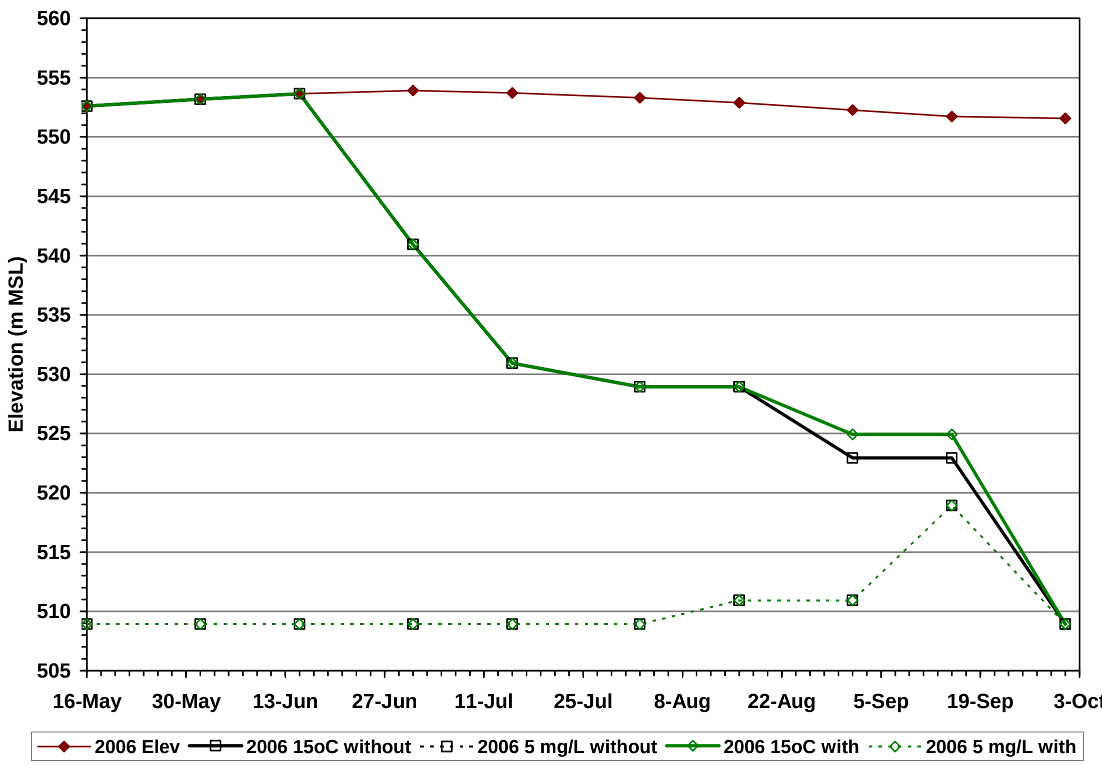


Figure 5-8. Elevation of simulated lake surface, 15°C temperature, and 5 mg/L dissolved oxygen isopleth during 2006 at station L1 - Government Bay with (green) and without (black) trash rack barriers.

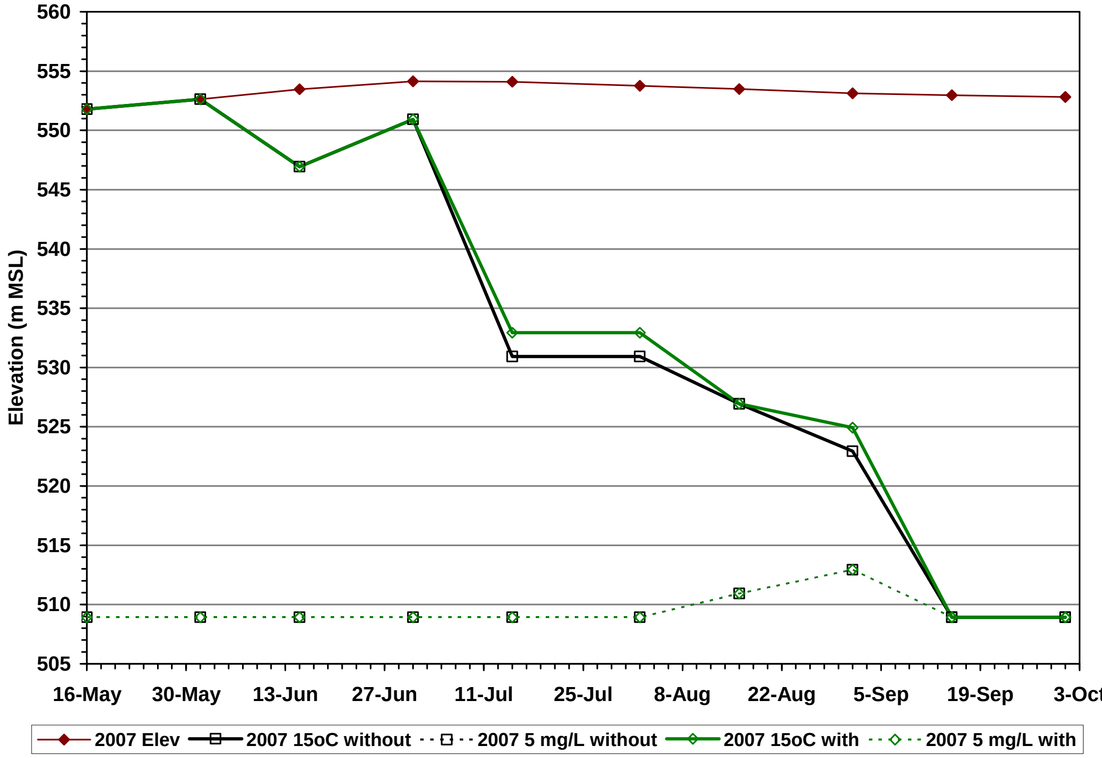


Figure 5-9. Elevation of simulated lake surface, 15°C temperature, and 5 mg/L dissolved oxygen isopleth during 2007 at station L1 - Government Bay with (green) and without (black) trash rack barriers.

5.1.3 IMPACT OF BARRIERS ON COLDWATER HABITAT VOLUME

The impact of trash rack intake barriers on CWH volume is quantified on water quality sampling dates and summarized in Table 5-1. Optimal CWH volume is expressed in MAF for the with- and without-intake barrier simulations, and the difference between the two are provided. In general the volume of CWH when intake barriers were simulated was greater than the volume of CWH without the intake barriers.

CWH savings induced by the simulated intake barriers were generally greatest from mid-August to early September when thermal stratification was at its greatest prior to the beginning of fall cooling and lake turnover. This coincides with the time period when CWH is stressed the most and is driven to the deepest regions of the reservoir in the old Missouri River channel and near Garrison Dam.

Minimum CWH for both cases are provided in the Minimum CWH row for each year. At minimum CWH, savings induced by the intake barriers was greatest in 2003, 2004, and 2006 and least in 2005 and 2007. CWH saved in 2003 was 0.461 MAF, while in 2007, the with-intake barrier simulation had 0.01 MAF less CWH than the without-intake barrier simulation.

Time series of optimal and total CWH are also plotted in Figures 5-10 through 5-14. Simulations with intake barrier water quality measures are represented as green lines in the figures; without are represented as black lines.

Table 5-1. Comparison of simulated Optimal CWH ($T < 15^oC$, DO > 5 mg/L) volume between simulations with and without intake barrier water quality measures.

Date	Simulated Optimal CWH, Million acre-feet (MAF)		
	With Intake Barriers	Without Intake Barriers	Difference
17 June 2003	9.606	9.618	-0.012
1 July 2003	5.722	5.576	0.146
16 July 2003	3.978	3.818	0.160
30 July 2003	3.337	3.114	0.223
12 August 2003	2.576	2.302	0.274
28 August 2003	1.870	1.512	0.358
9 September 2003	0.928	0.397	0.531
23 September 2003	0.771	0.573	0.198
Minimum CWH	0.610	0.149	0.461
24 June 2004	10.953	10.934	0.019
19 July 2004	4.085	4.084	0.001
24 August 2004	1.437	1.245	0.192
8 September 2004	0.866	0.379	0.487
20 September 2004	0.352	0.043	0.309
Minimum CWH	0.211	0.030	0.181
22 June 2005	5.433	5.438	-0.005
20 July 2005	2.482	2.482	0.000
24 August 2005	1.194	1.128	0.066
19 September 2005	0.154	0.120	0.034
Minimum CWH	0.036	0.027	0.009
20 June 2006	6.733	6.661	0.072
25 July 2006	2.604	2.604	0.000
29 August 2006	0.888	0.797	0.091
13 September 2006	0.400	0.246	0.154
3 October 2006	1.444	1.432	0.012
Minimum CWH	0.192	0.071	0.121
22 May 2007	9.945	9.945	0.000
27 June 2007	4.016	4.002	0.014
24 July 2007	2.183	2.088	0.095
21 August 2007	1.083	0.850	0.235
11 September 2007	0.085	0.132	-0.047
25 September 2007	0.660	0.721	-0.061
Minimum CWH	0.025	0.035	-0.010

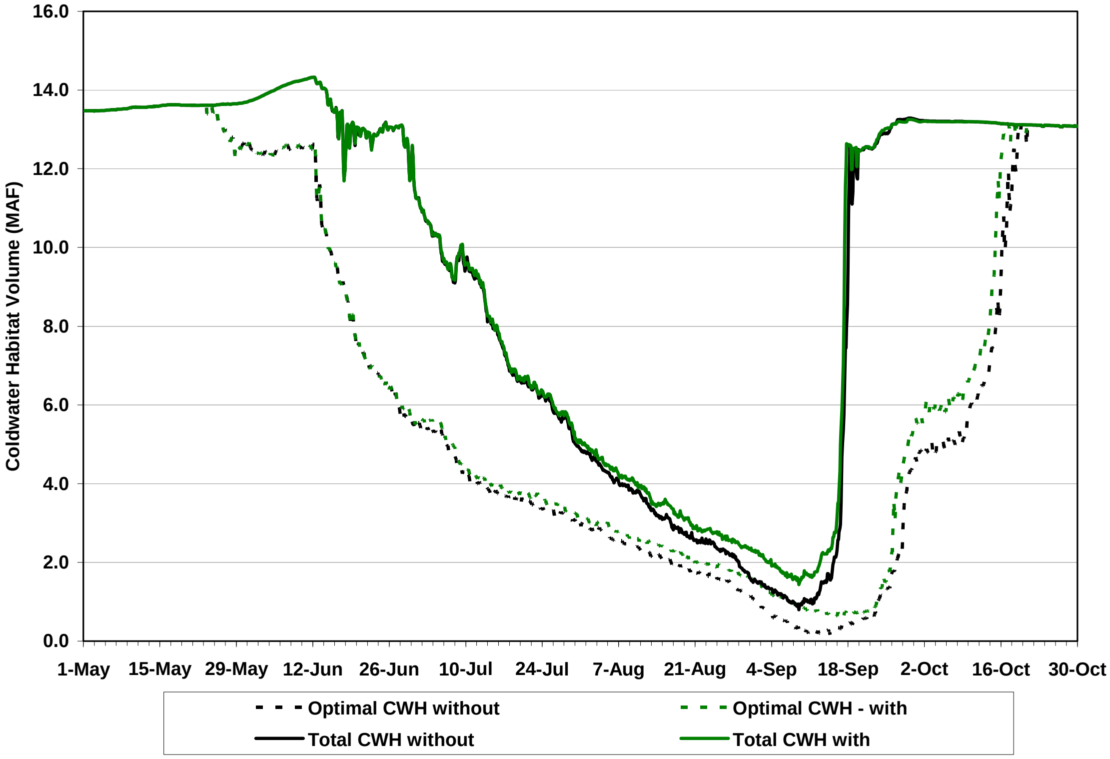


Figure 5-10. Simulated volume of optimal and total CWH in Lake Sakakawea during 2003 simulated with (green) and without (black) trash rack barriers.

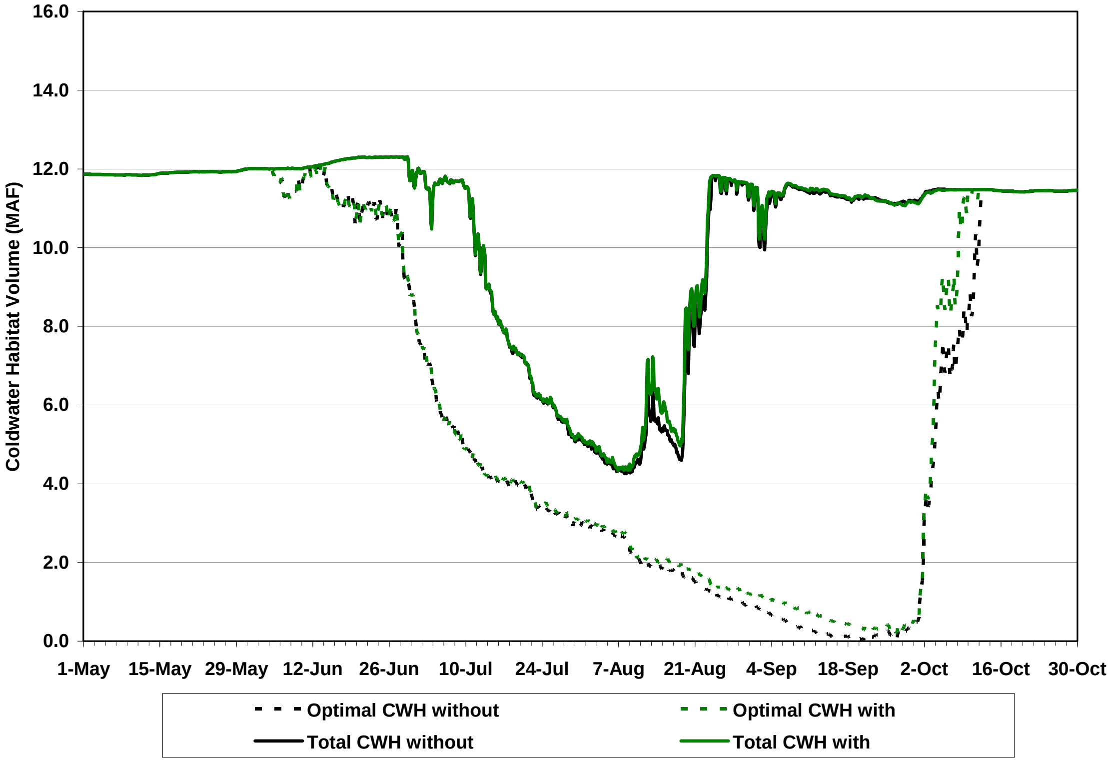


Figure 5-11. Simulated volume of optimal and total CWH in Lake Sakakawea during 2004 simulated with (green) and without (black) trash rack barriers.

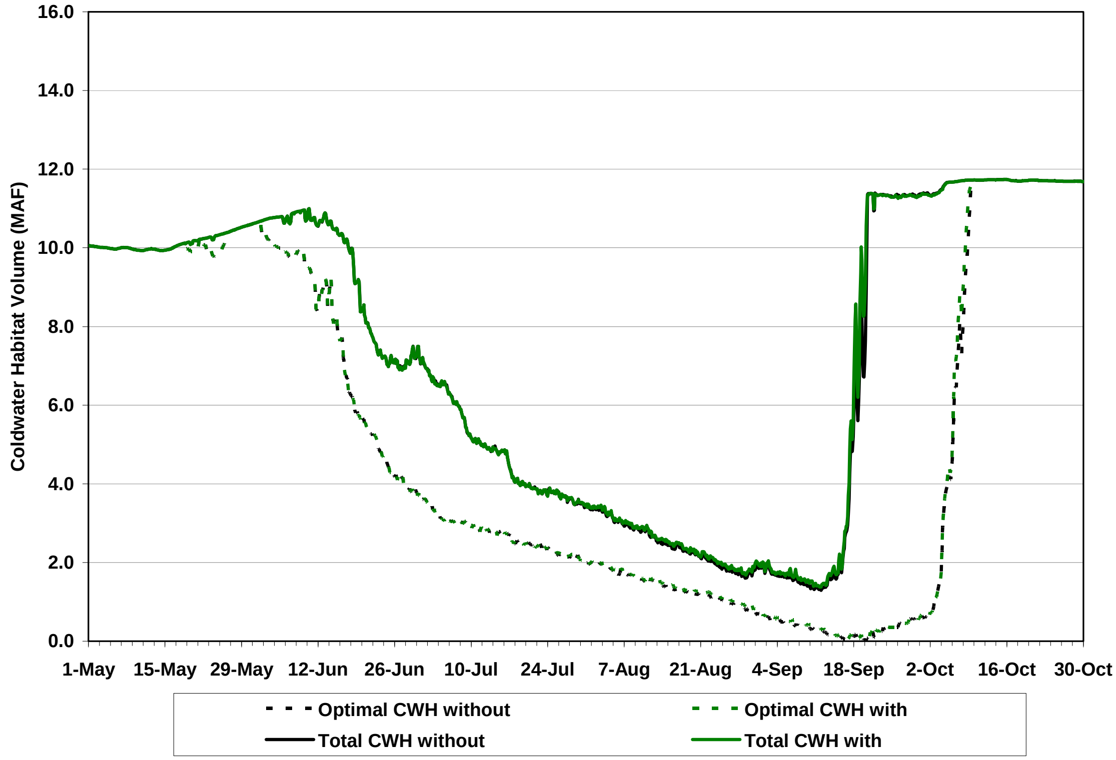


Figure 5-12. Simulated volume of optimal and total CWH in Lake Sakakawea during 2005 simulated with (green) and without (black) trash rack barriers.

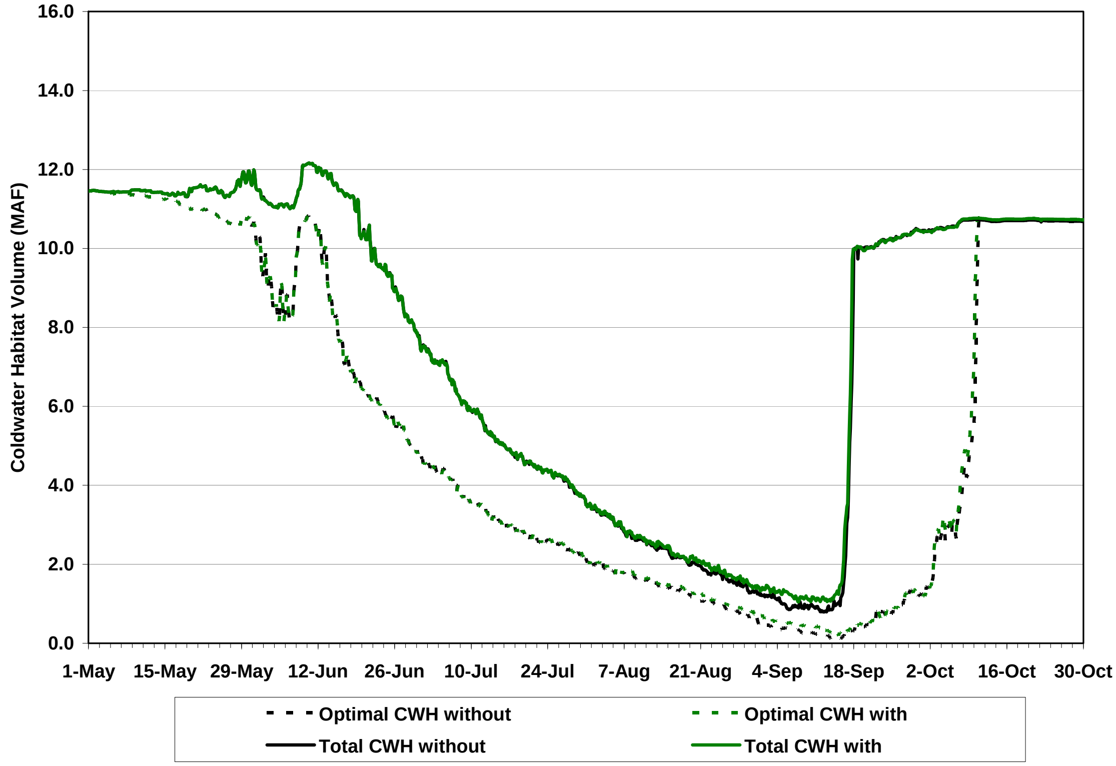


Figure 5-13. Simulated volume of optimal and total CWH in Lake Sakakawea during 2006 simulated with (green) and without (black) trash rack barriers.

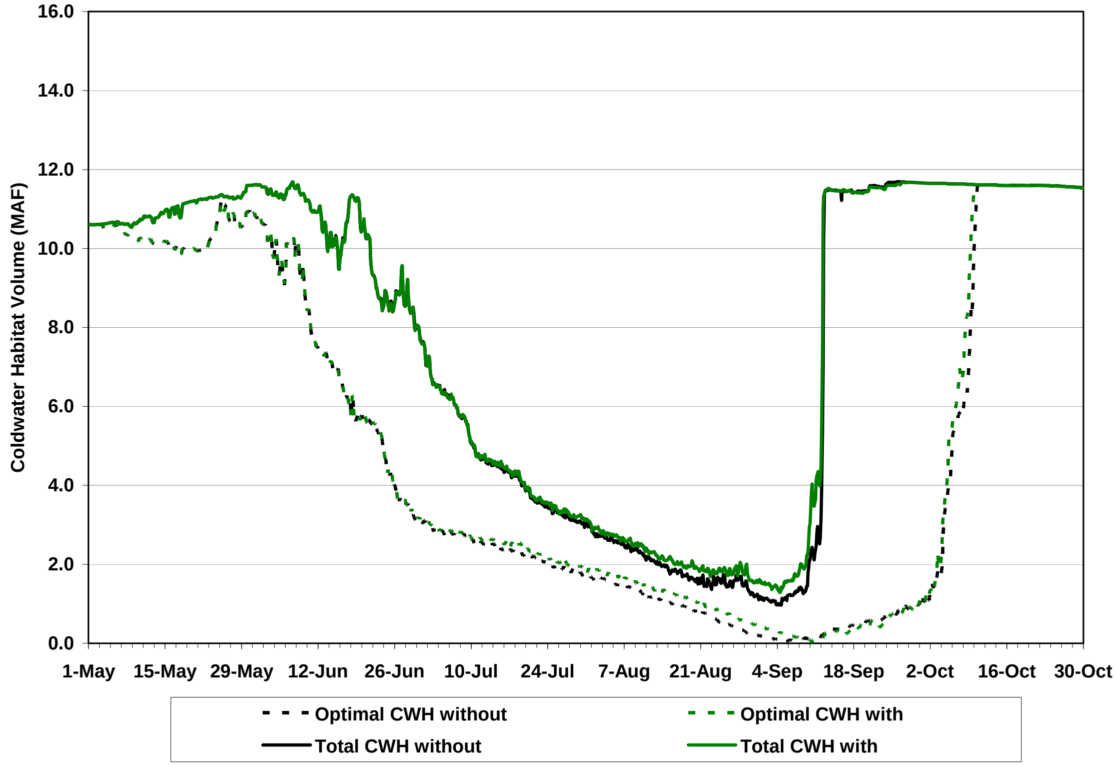


Figure 5-14. Simulated volume of optimal and total CWH in Lake Sakakawea during 2007 simulated with (green) and without (black) trash rack barriers.

5.2 RESERVOIR OUTFLOW PEAKING

The impact of outflow peaking on reservoir water temperature, dissolved oxygen, and CWH was evaluated by comparing simulations that incorporated non-peaked and peaked powerhouse outflows in simulation years 2005, 2006, and 2007. Peaked outflows were represented through hourly outflows measured in the penstocks, while non-peaked outflows were represented by average daily outflows for all releases. Simulations were also performed for conditions with and without the plywood intake barriers; however, the impact of peaking was insensitive to the presence of the barriers. Results of the simulations are shown for the 2006 simulation year without intake barriers scenario using an intake centerline elevation of 513.6 m (1685 ft).

5.2.1 IMPACT OF OUTFLOW PEAKING ON WATER QUALITY

5.2.1.1 Temperature

Flow peaking did not impact lake temperatures near the intake tunnel centerline elevation of 513.6 m (1685.0 ft) at site L1 (Government Bay) during all years including 2006 shown in Figure 5-15. This model location is approximately 3.5 km (2.2 miles) along the old Missouri River channel upstream from the powerhouse intake tower. Due to limitations of the model resolution and its two-dimensional computational technique, it is unlikely that temperature could be impacted over the expanse of the reservoir; however, a temperature response was observed in discharge water (Figure 5-16). The model simulated higher discharge temperatures as a result of peak discharges drawing warmer water from higher elevations within the reservoir. A similar but opposite outcome occurred when lower discharges drew colder, lower elevation water from the reservoir during the low outflow periods.

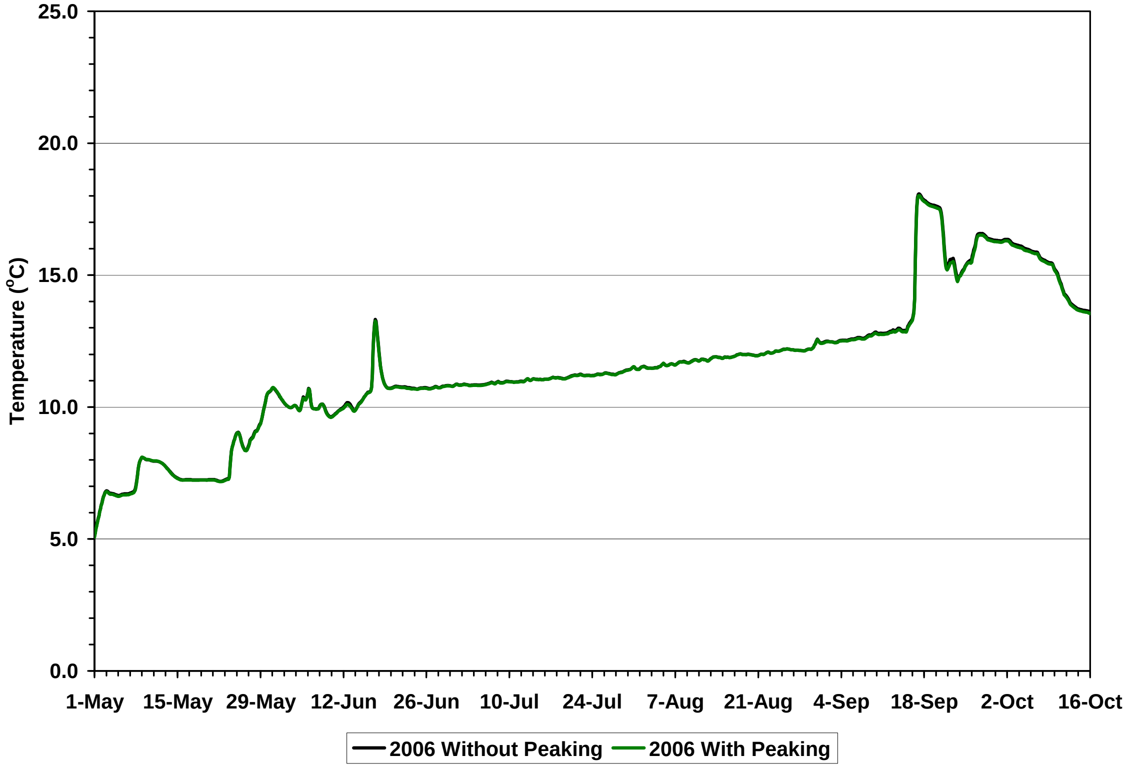


Figure 5-15. 2006 simulated water temperatures near the intake tunnel centerline elevation 513.6 m (1685.0 ft) at site L1 (Government Bay) without (black) and with (green) implemented flow peaking.

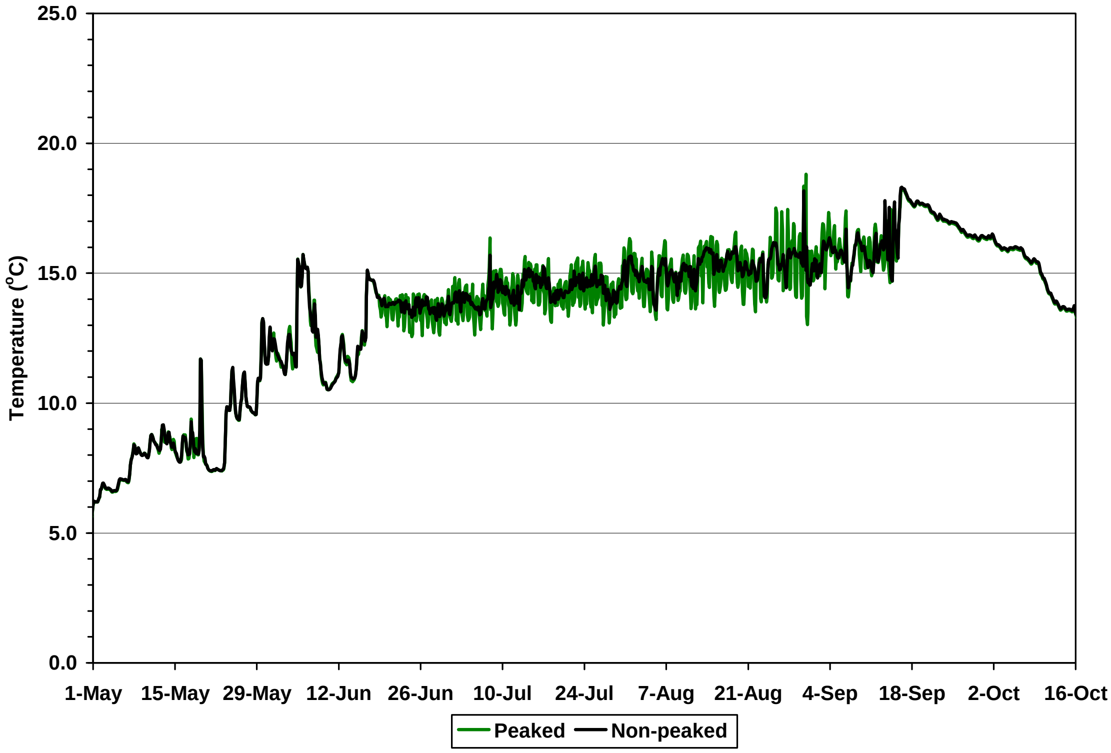


Figure 5-16. 2006 simulated water temperatures in the powerhouse discharge without (black) and with (green) implemented flow peaking.

5.2.1.2 <u>Dissolved Oxygen</u>

Flow peaking marginally impacted DO concentrations near the intake tunnel centerline elevation of 513.6 m (1685.0 ft) at site L1 (Government Bay) during all years including 2006 shown in Figure 5-17. DO concentrations of the peaked outflow simulations were slightly lower than non-peaked concentrations from the end of August until mid-September; but, at that point DO concentrations were near or less than 5 mg/L in both peaked and non-peaked simulations.

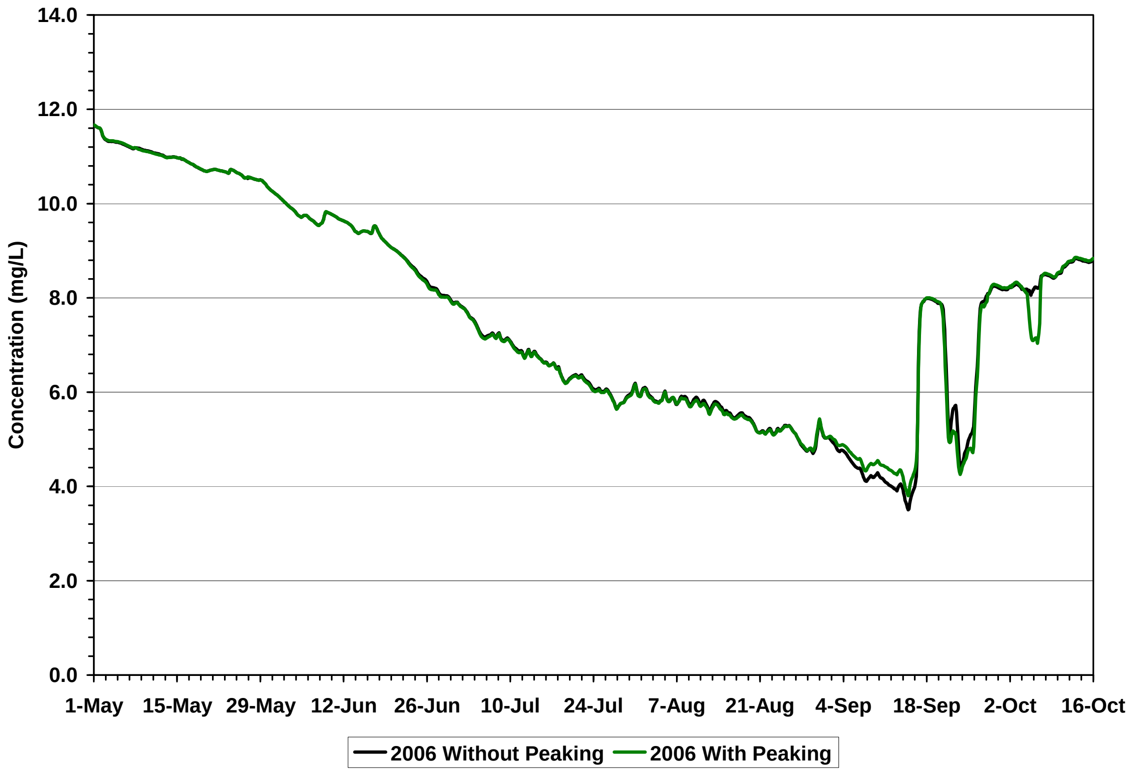


Figure 5-17. 2006 simulated dissolved oxygen concentrations near the intake tunnel centerline elevation 513.6 m (1685.0 ft) at site L1 (Government Bay) without (black) and with (green) implemented flow peaking.

5.2.2 IMPACT OF OUTFLOW PEAKING ON COLDWATER HABITAT CRITERIA DEPTH

Based on a comparison of the simulated temperature time series data, 15 degrees C temperature depth, and 5 mg/L DO concentration depth for with and without flow peaking scenarios, flow peaking had no perceivable impact on CWH criteria depth. Figures 5-16 and 5-17, comparing temperature and DO concentration of the two scenarios, show very limited differences in temperature and DO in 2006. Figure 5-18 is a plot of 15 degrees C and 5 mg/L DO concentration depths versus time of year at station L1 (Government Bay). The Lake Sakakawea model is constructed with a two-meter vertical layer resolution; therefore, vertical temperature profiles do not precisely portray temperature behavior. On September 15 the simulated depth of the 5 mg/L DO isopleths in the flow peaking alternative was lower than in the non-peaking alternative indicating a potential DO increase at least in 2006 due to flow peaking. The amount of data indicating that CWH is saved due to flow peaking is minimal and the impact may be negligible. Further modeling of flow peaking under additional pool elevation conditions and field observations are recommended to draw a more definitive conclusion.

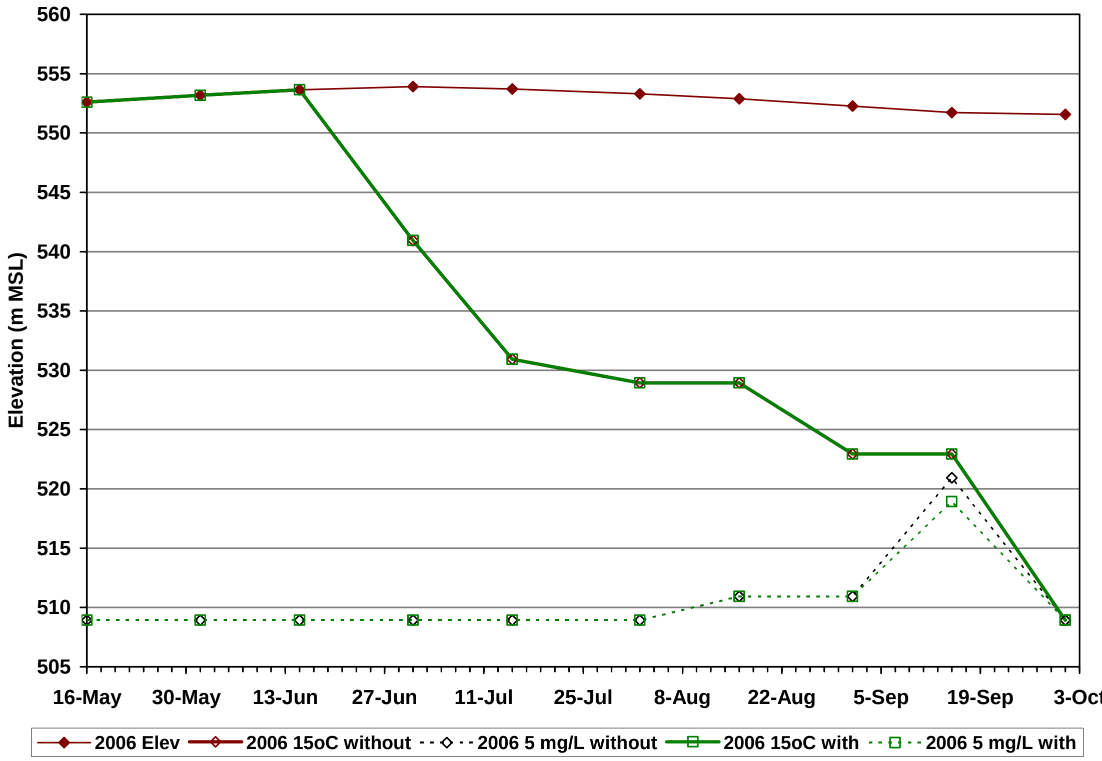


Figure 5-18. Elevation of 2006 simulated lake surface, 15°C water temperature, and 5 mg/L dissolved oxygen isopleths at station L1 (Government Bay) without (black) and with (green) flow peaking operations.

5.2.3 IMPACT OF OUTFLOW PEAKING ON COLDWATER HABITAT VOLUME

Based on a comparison of with and without outflow peaking simulations, flow peaking had no significant impact on both optimal and total CWH volumes in Lake Sakakawea. Figure 5-19 is a plot of optimal and total CWH volumes in 2006 versus time of year at station L1 (Government Bay) demonstrating the insignificant difference in volumes between the operating scenarios. The other simulation years show similar results, but are not plotted in this report.

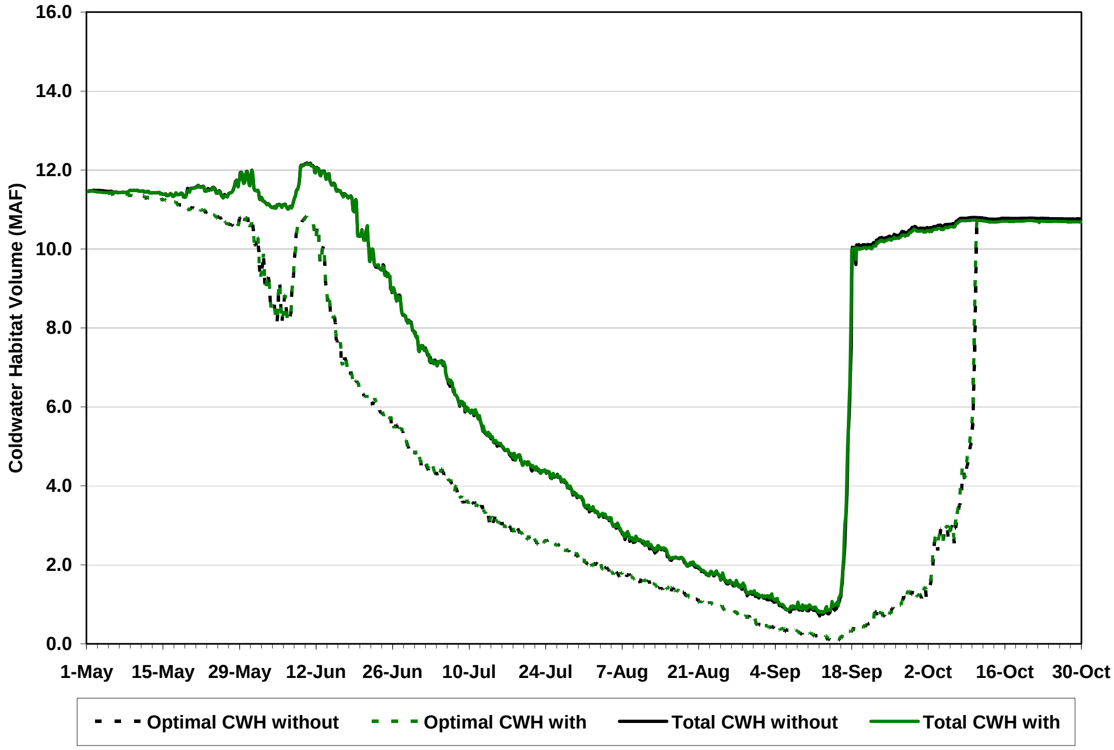


Figure 5-19. Simulated volume of optimal and total CWH in Lake Sakakawea during 2006 simulated without (black) and with (green) outflow peaking.

5.3 HEAD GATE CLOSURE

The CE-QUAL-W2 model is a two-dimensional model that performs laterally averaged computations within each segment layer. Segment layers near the dam vary in width from 142 m (469 ft) to 2138 m (7014 ft). The size of the inlet is small compared to layer widths and would behave like a point sink. Computationally, the model cannot accurately model closure of a head gate due to the lateral averaging limitation; therefore, the head gate closure water quality management measure was not evaluated with the model.

6 ASSESSMENT OF A HYPOTHETICAL HIGH-LEVEL RESERVOIR WITHDRAWAL FOR POWER PRODUCTION

6.1 HIGH-LEVEL RESERVOIR WITHDRAWAL

A hypothetical high-level reservoir withdrawal was evaluated using the reservoir model. The high-level outlet eliminated all low-level (existing) reservoir outlets, and raised the lower intake elevation in the towers to 541 m (1775 ft) with an outlet centerline of 548.6 m (1800 ft). The high-level intake was set near this elevation because elevation 541 m (1775 ft) is the top of the currently designated Permanent Pool Zone for Lake Sakakawea. A high-level reservoir withdrawal from each of the five power intake towers could potentially increase the temperature of withdrawal water preserving colder low-level reservoir water.

6.2 IMPACTS OF HIGH-LEVEL WITHDRAWAL

Water temperature and nutrients including dissolved oxygen were simulated using the hypothetical high-level outlet in simulation years 2003 through 2007. The results are summarized into three sets of figures focusing on reservoir withdrawal temperature, the elevation (depth) within the water column of optimum coldwater habitat criteria and the volume of coldwater habitat in the reservoir as a result of the simulated conditions.

6.2.1 RESERVOIR DISCHARGE TEMPERATURE

Reservoir discharge water temperatures from the high-level outlet compared to the normal outlet were 3.0 to 6.0 degrees Celsius higher in all reservoir temperature simulations. This increase in discharge temperature from a normal to high-level withdrawal is shown in a plot of 2006 simulated temperatures in Figure 6-1. The hypothetical high-level withdrawal centerline 548.6 m (1800 ft) sits above the temperature thermocline, thus allowing warmer high-level water to be withdrawn from the reservoir. From late June to early September, high-level withdrawal temperatures were 3.0 to 5.0 degrees Celsius higher than normal-level withdrawal temperatures.

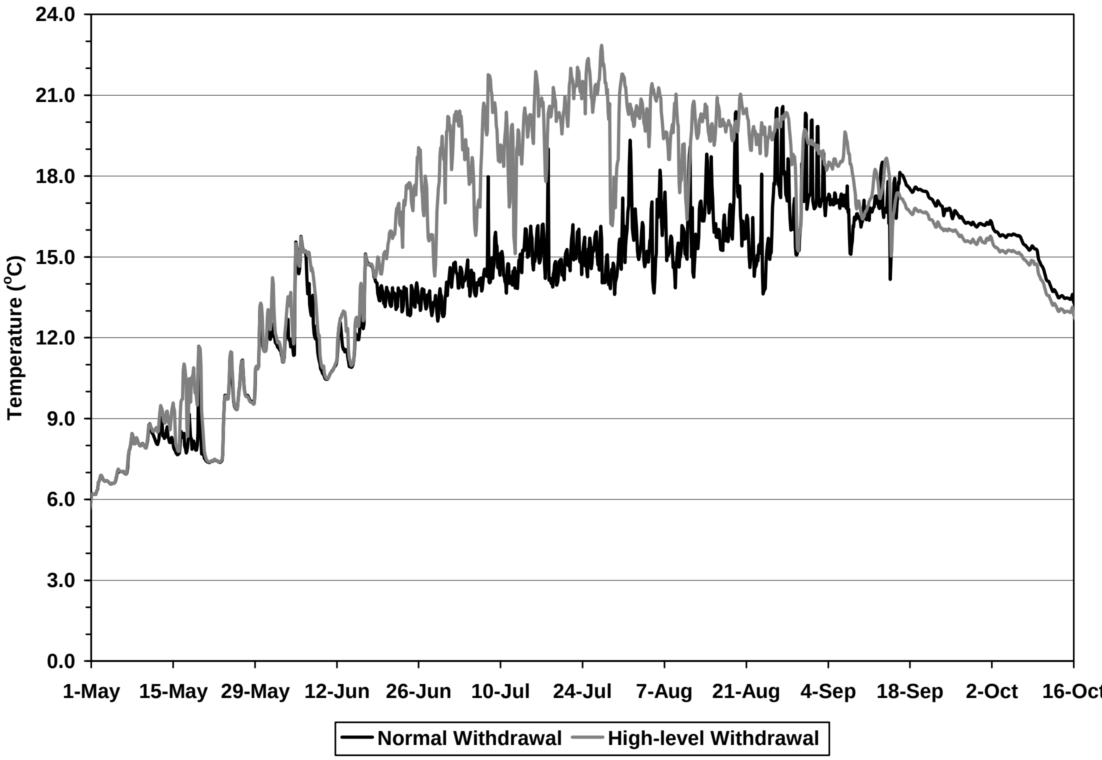


Figure 6-1. 2006 simulated water temperatures in the powerhouse discharge with a normal withdrawal (black) and a high-level withdrawal (gray).

6.2.2 RESERVOIR COLDWATER HABITAT CRITERIA DEPTH

Simulated CWH criteria isotherm (15 degrees C) and DO (5 mg/L) isopleth elevations are plotted versus time for the low-level withdrawal (no plywood barriers) and the high-level reservoir withdrawal scenarios in Figures 6-2 through 6-6.

Compared to the lower-level outlet, the high-level withdrawal further limited the depth that the 15 degrees C isotherm descended into the water column because higher-level/warmer water was withdrawn from the reservoir, preserving the colder water.

With regard to the elevation of the 5 mg/L dissolved oxygen isopleths, the simulated results were mixed. The depth of the isopleth in 2003 and 2007 did not deviate from results of the low-level withdrawal simulations. In 2004 and 2006 the elevation of the DO isopleths with the high-level outlet was higher than the low-level outlet simulation indicating that DO water quality below the isopleths was below the 5 mg/L level and worse than the other simulation. DO degradation due to organic matter decomposition occurred because oxygenated water from higher levels did not descend to the bottom to replace low-level reservoir water. In 2005 the high-level withdrawal DO isopleth remained at the same elevation as the low-level outlet simulation except on September 16 when it was below the other simulation.

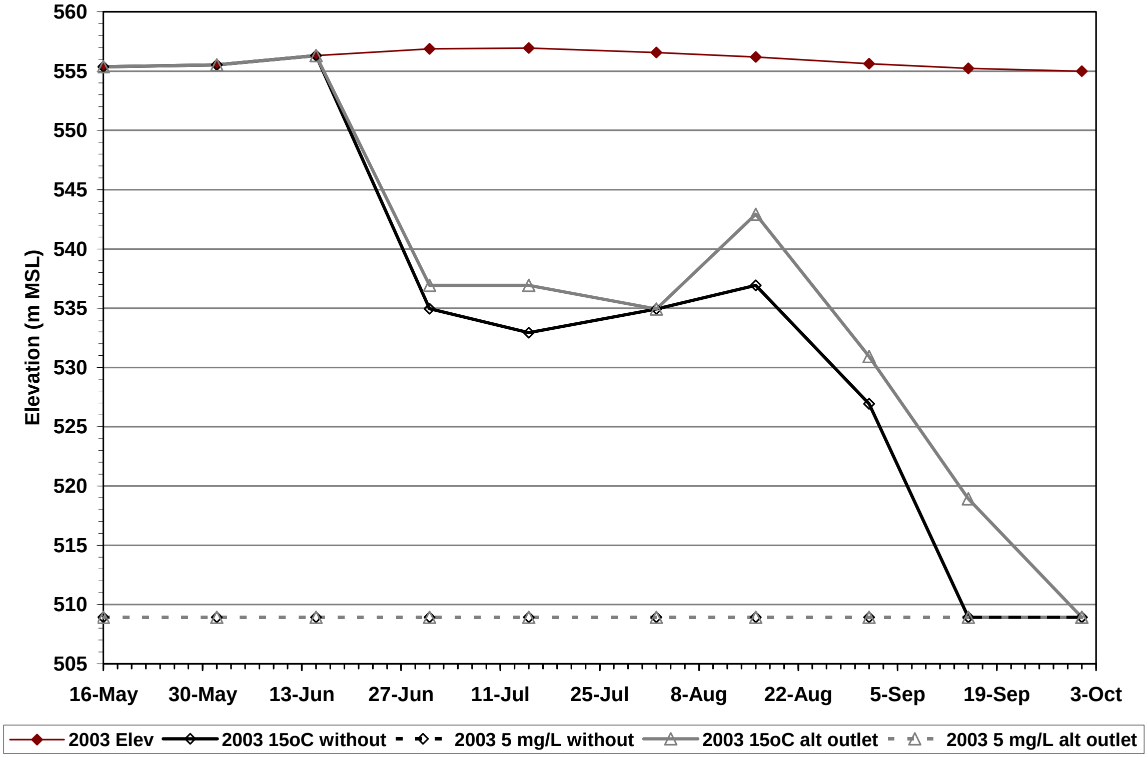


Figure 6-2. Elevation of 2003 simulated lake surface, 15^{o}C temperature isotherm, and 5 mg/L dissolved oxygen isopleth at station L1, without (black) and with (gray) a high-level reservoir withdrawal.

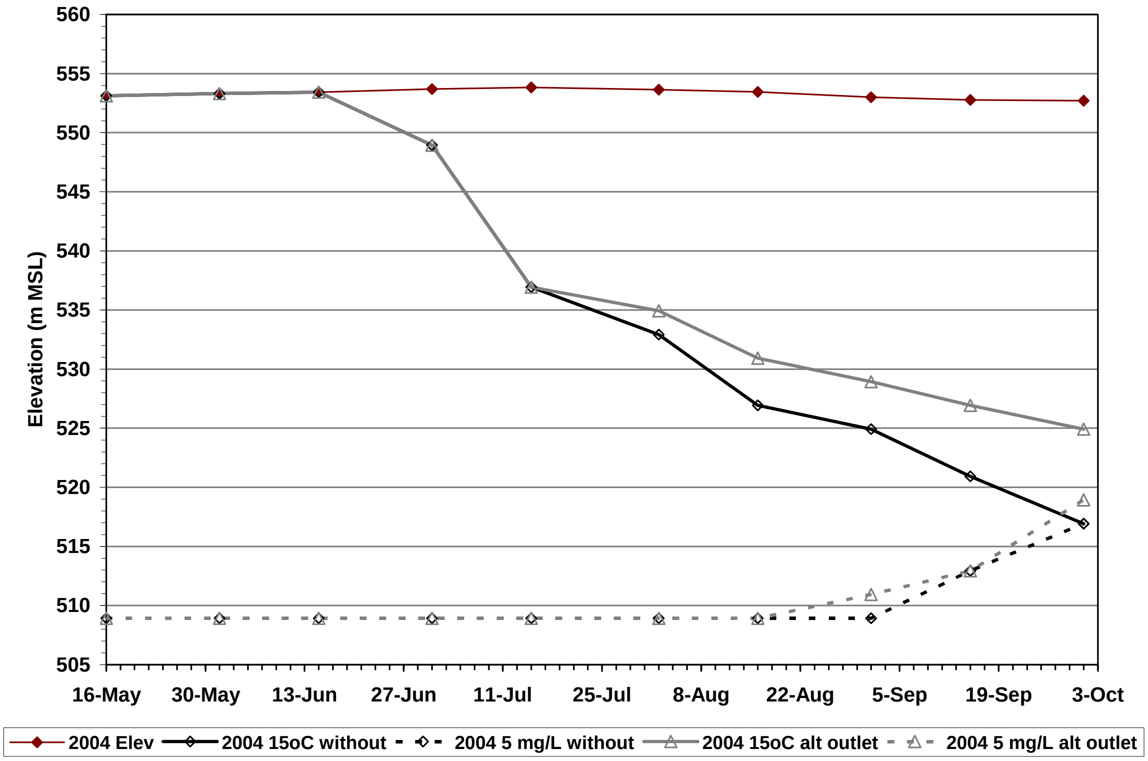


Figure 6-3. Elevation of 2004 simulated lake surface, 15^{o}C temperature isotherm, and 5 mg/L dissolved oxygen isopleth at station L1, without (black) and with (gray) a high-level reservoir withdrawal.

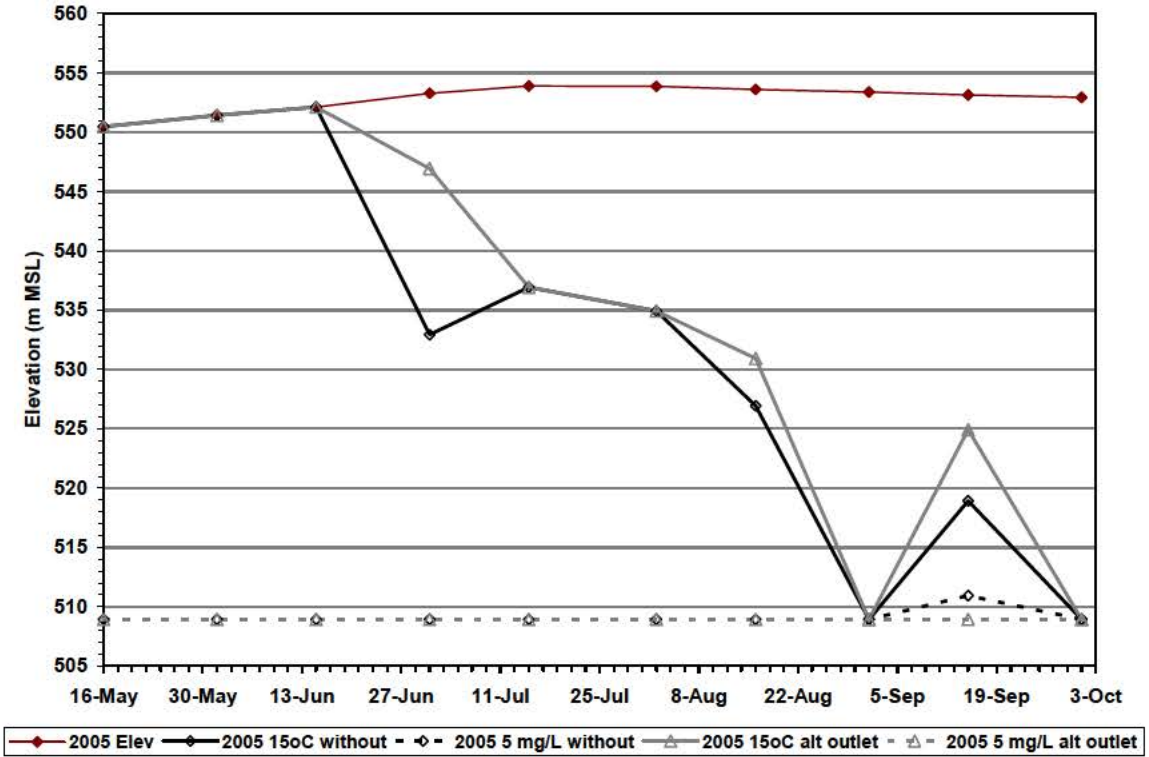


Figure 6-4. Elevation of 2005 simulated lake surface, 15°C temperature isotherm, and 5 mg/L dissolved oxygen isopleth at station L1, without (black) and with (gray) a high-level reservoir withdrawal.

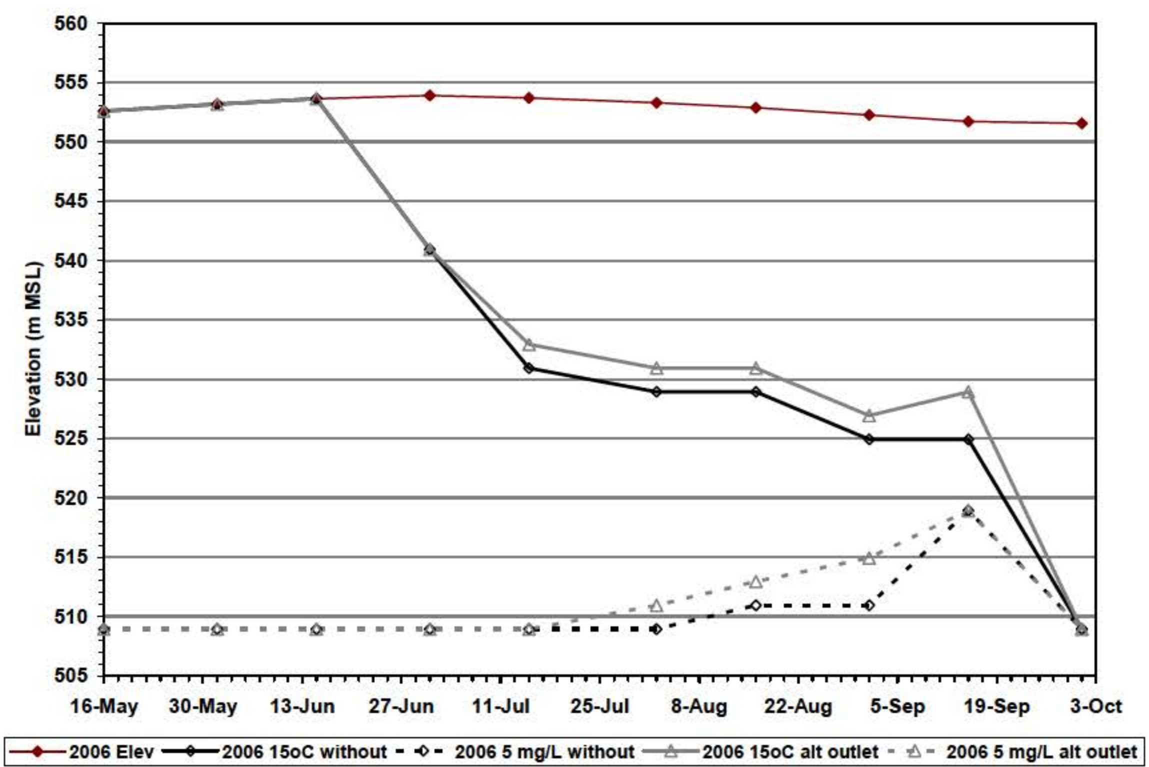


Figure 6-5. Elevation of 2006 simulated lake surface, 15°C temperature isotherm, and 5 mg/L dissolved oxygen isopleth at station L1, without (black) and with (gray) a high-level reservoir withdrawal.

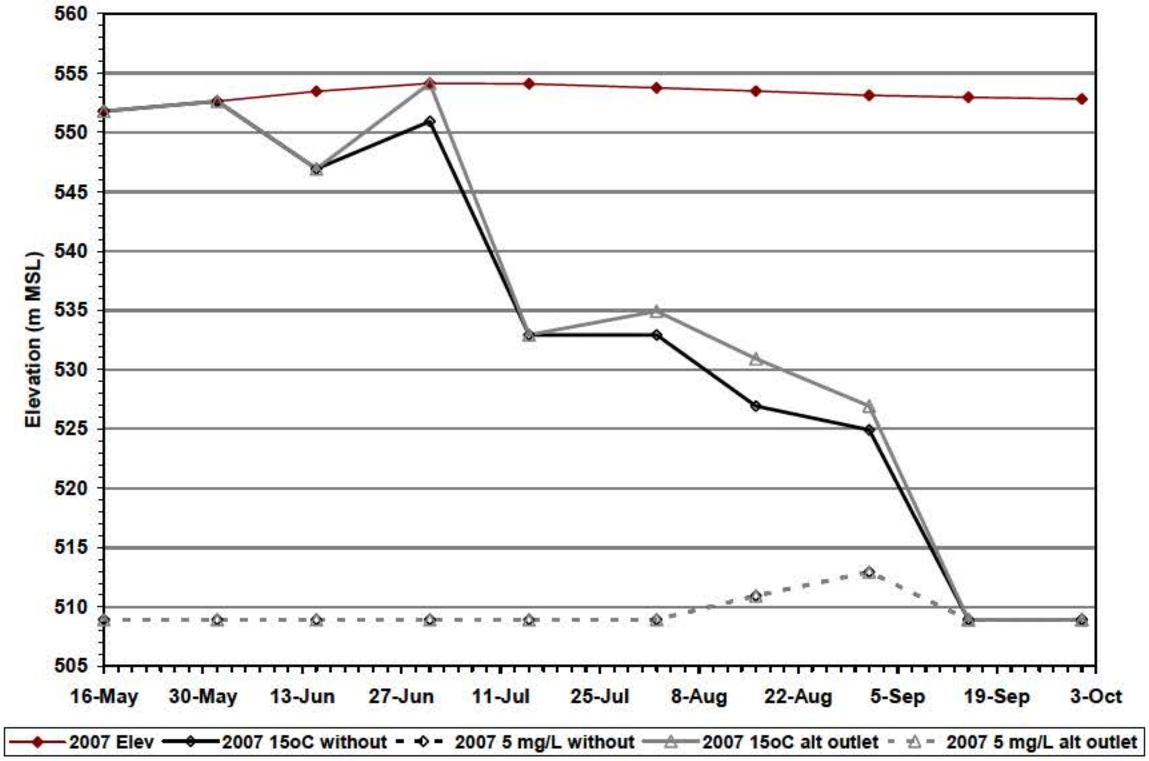


Figure 6-6. Elevation of 2007 simulated lake surface, 15°C temperature isotherm, and 5 mg/L dissolved oxygen isopleth at station L1, without (black) and with (gray) a high-level reservoir withdrawal.

6.2.3 Coldwater Habitat Volume

The impact of a hypothetical high-level withdrawal versus a low-level withdrawal is quantified in terms of optimal coldwater habitat volume in Table 6-1. In general the simulations indicate the high-level withdrawal preserves more coldwater CWH volume than both the intake barrier alternative and the normal low-level withdrawal. Simulated CWH savings during the 2003 to 2007 simulation years when CWH volumes reached minimums ranged from 0.390 to 1.453 million acre-feet.

Figures 6-7 through 6-11 are time series plots of the simulated total and simulated optimal CWH volumes in 2003, 2004, 2005, 2006, and 2007 comparing the high-level withdrawal with the low-level withdrawal. In all cases the total and optimal CWH volumes in the high-level withdrawal (alt outlet) simulations were greater than the low-level withdrawal. A hypothetical high-level reservoir withdrawal could provide an advantage in maintaining and preserving both total and optimal CWH in Lake Sakakawea, while providing warmer water to the Missouri River downstream of Garrison Dam. It also possibly reduces the occurrence of low DO conditions in the river in late summer when degraded DO conditions occur near the bottom of Lake Sakakawea at the dam.

Table 6-1. Comparison of simulated Optimal CWH (T < 15°C, DO > 5 mg/L) volume between simulations with no withdrawal modification and a hypothetical high-level reservoir withdrawal.

Date	Simulated Optimal CWH, Million acre-feet (MAF)			
	Intake Barriers	**High-Level Withdrawal**	**Bottom Withdrawl**	**High-Level/ Bottom Withdrawal Difference**
17 June 2003	9.606	9.618	9.618	0.000
1 July 2003	5.722	5.894	5.576	0.318
16 July 2003	3.978	4.235	3.818	0.417
30 July 2003	3.337	3.887	3.114	0.773
12 August 2003	2.576	3.522	2.302	1.220
28 August 2003	1.870	2.573	1.512	1.061
9 September 2003	0.928	2.060	0.397	1.663
23 September 2003	0.771	1.665	0.573	1.092
Minimum CWH	0.610	1.631	0.149	1.482
24 June 2004	10.953	10.972	10.934	0.038
19 July 2004	4.085	4.183	4.084	0.099
24 August 2004	1.437	1.800	1.245	0.555
8 September 2004	0.866	1.322	0.379	0.943
20 September 2004	0.352	0.696	0.043	0.653
Minimum CWH	0.211	0.554	0.030	0.524
22 June 2005	5.433	5.489	5.438	0.051
20 July 2005	2.482	2.799	2.482	0.317
24 August 2005	1.194	1.929	1.128	0.801
19 September 2005	0.154	0.954	0.120	0.834
Minimum CWH	0.036	0.706	0.027	0.679
20 June 2006	6.733	6.696	6.661	0.035
25 July 2006	2.604	3.096	2.604	0.492
29 August 2006	0.888	1.745	0.797	0.948
13 September 2006	0.400	1.151	0.246	0.905
3 October 2006	1.444	2.948	1.432	1.516
Minimum CWH	0.192	0.839	0.071	0.768
22 May 2007	9.945	9.946	9.945	0.001
27 June 2007	4.016	4.107	4.002	0.105
24 July 2007	2.183	2.499	2.088	0.411
21 August 2007	1.083	1.513	0.850	0.663
11 September 2007	0.085	0.509	0.132	0.377
25 September 2007	0.660	0.721	0.721	0.000
Minimum CWH	0.025	0.435	0.035	0.400

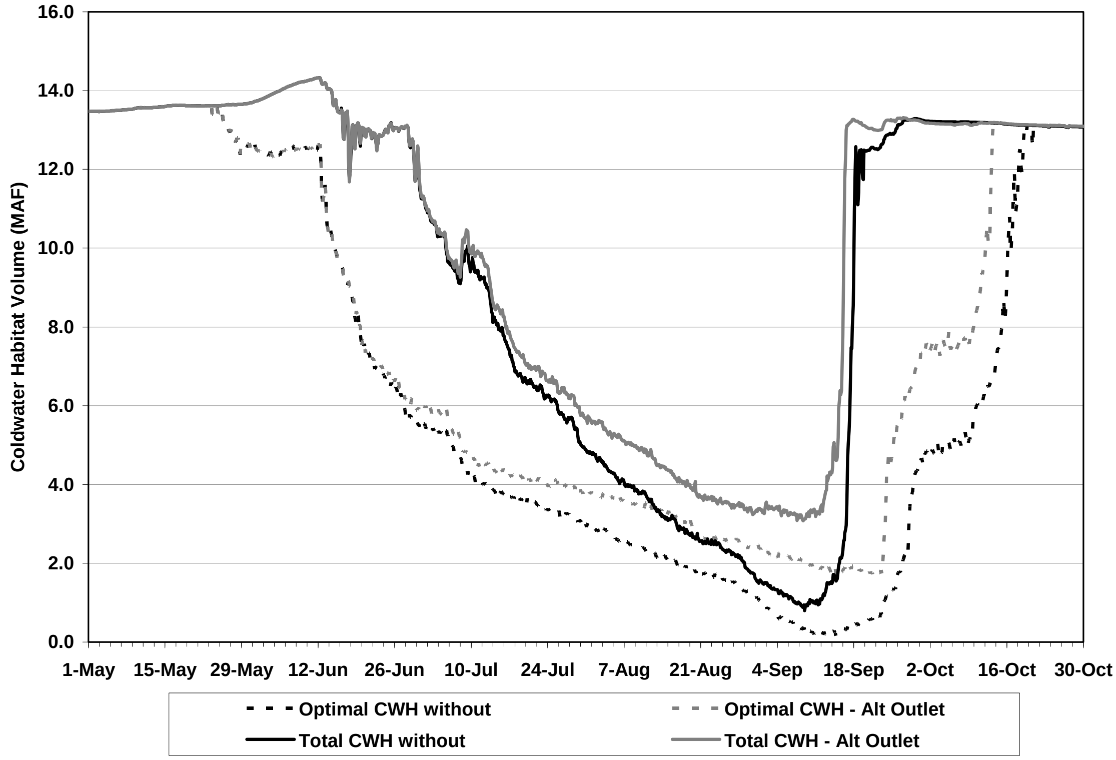


Figure 6-7. Simulated volume of optimal and total CWH in Lake Sakakawea during 2003, without (black) and with (gray) a high-level reservoir withdrawal.

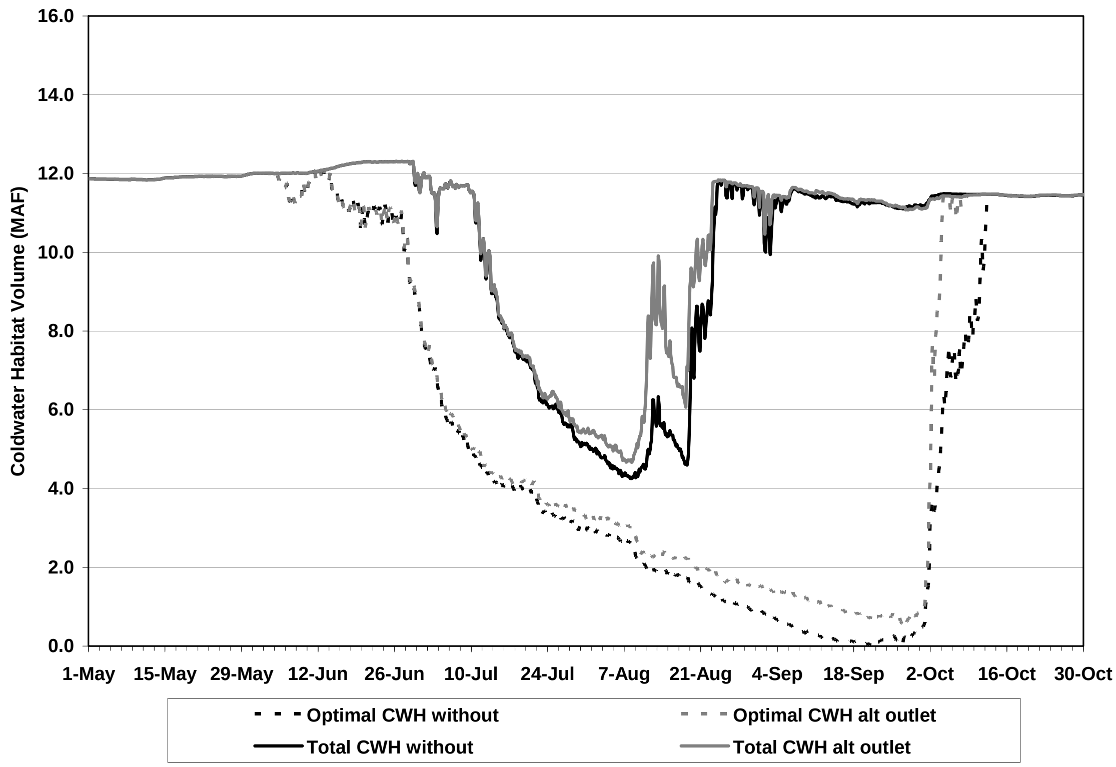


Figure 6-8. Simulated volume of optimal and total CWH in Lake Sakakawea during 2004, without (black) and with (gray) a high-level reservoir withdrawal.

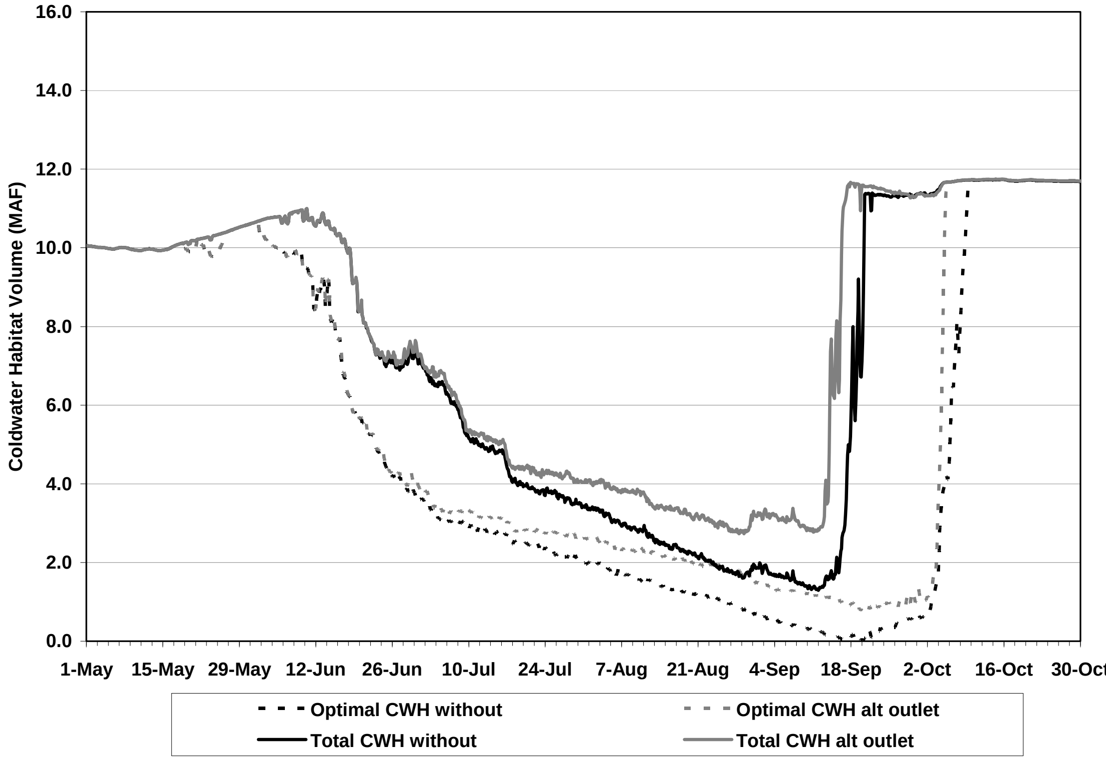


Figure 6-9. Simulated volume of optimal and total CWH in Lake Sakakawea during 2005, without (black) and with (gray) a high-level reservoir withdrawal.

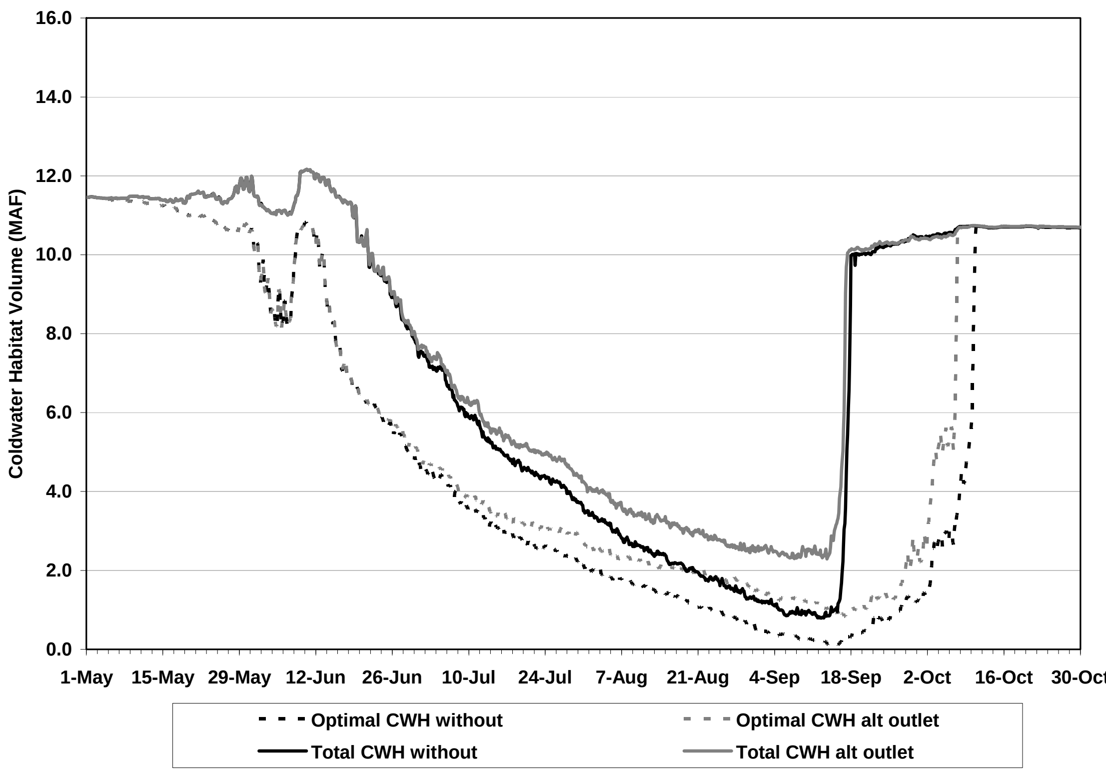


Figure 6-10. Simulated volume of optimal and total CWH in Lake Sakakawea during 2006, without (black) and with (gray) a high-level reservoir withdrawal.

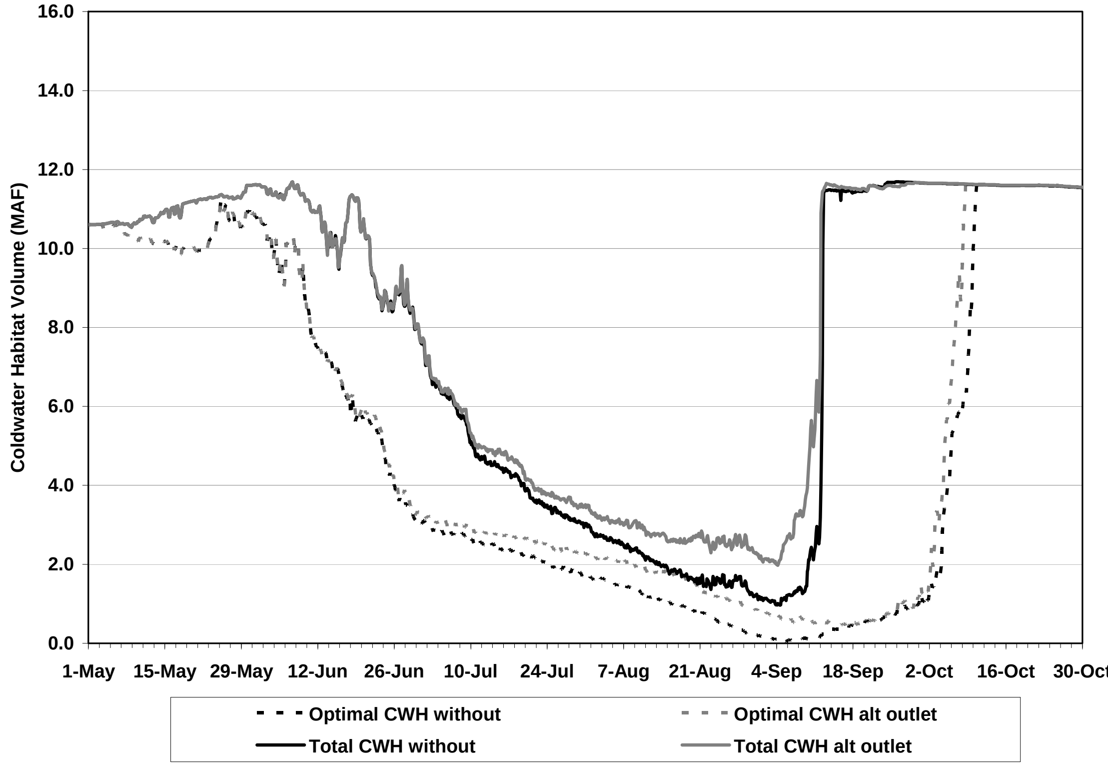


Figure 6-11. Simulated volume of optimal and total CWH in Lake Sakakawea during 2007, without (black) and with (gray) a high-level reservoir withdrawal.

7 FUTURE MODEL APPLICATIONS

7.1 IMPACT OF RESERVOIR STORAGE/POOL ELEVATION ON COLDWATER HABITAT

Low reservoir storage or pool elevation due to ongoing drought conditions is one of the causes of optimal CWH depletion during the periods of maximum stratification that occur in late summer in Lake Sakakawea. From 2003 to 2007, pool elevations have ranged from 1805.8 ft (550.4 m) to 1827.3 ft (557.0 m). The base of the flood control pool elevation is 1837.5 ft (560.1 m) and the average annual pool elevation from 1967 to 1997 was 1838.2 ft (560.3 m) (MRR RCC, 1999). Water quality data since 2003 and calibrated water quality and temperature simulations portray Lake Sakakawea in a low pool drought affected state.

In order to accurately assess the impacts of low storage and pool elevations, water quality data through water quality surveys and reservoir simulations is needed from normal and high pool states. Additional simulations at median, low pool (lower decile) and high pool (upper decile) states should be performed to understand the sensitivity of water quality and CWH to pool elevations. The model could also be used to identify pool elevation or storage thresholds where CWH depletion becomes an issue.

7.2 IMPACT OF VARIABLE INTAKE BARRIER OPERATION

Future simulations of Lake Sakakawea should evaluate the impact of variable intake barrier operation on CWH and water quality. Intake barrier operations were varied to a very limited degree in the Garrison field tests from 2005 to 2007; therefore, some variables that could be evaluated include time of placement, number of intakes on which barriers are placed, and barrier dimensions (elevation of implementation).

7.3 RESERVOIR REGULATION IMPACTS TO WATER QUALITY

A long range goal of reservoir water quality modeling is to evaluate water quality impacts in the Mainstem reservoirs as a result of system-wide operating decisions. For example a system of reservoir and river models linked in series could demonstrate the water quality impacts of storage unbalancing that regularly is performed in the upper three reservoirs, or the impact of water quality measures on the entire system. Considering the growing demand for recreational, wildlife habitat, and water supply uses a system of models would serve as a decision support system for future water allocations and operations.

8 REFERENCES

Cole, Thomas M., and Wells S.A.. 2003. CE-QUAL-W2: A Two-Dimensional, Laterally Average, Hydrodynamic and Water Quality Model, Version 3.2, User Manual. U.S. Army Corps of Engineers, Department of the Army, Washington, D.C.

Cole, Thomas M., Schneider, M.L., Skogerboe, J.G., Heath, R.E., and Turner, H.O. 1994. Temperature and dissolved oxygen simulations for the Upper Missouri River Reservoirs, Miscellaneous Report, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

U.S. Army Corps of Engineers. 1987. Engineer Manual 1110-2-1201, Engineering and Design – Reservoir Water Quality Analysis. U.S. Army Corps of Engineers, Department of the Army, Washington, D.C.

U.S. Army Corps of Engineers. 2004. Missouri River Mainstem Reservoir System, Master Water Control Manual, Missouri River Basin (March 2004). Reservoir Control Center, Northwestern Division – Missouri River Basin, U.S. Army Corps of Engineers, Department of the Army. Omaha, Nebraska.

U.S. Army Corps of Engineers, Missouri River Region Reservoir Control Center. 1999. Missouri River Main Stem Reservoirs Hydrologic Statistics, RCC Technical Report F-99. U.S. Army Corps of Engineers, Department of the Army, Omaha, Nebraska.

U.S. Army Corps of Engineers, Omaha District. 2006. Water Quality Special Study Report. Water Quality Conditions Monitored at the Corps' Garrison Project in North Dakota during the 3-year Period 2003 through 2005. U.S. Army Corps of Engineers, Department of the Army, Omaha, Nebraska.

U.S. Army Corps of Engineers, Omaha District. 2008. Program Management Plan for Implementing the Omaha District's Water Quality Management Program. U.S. Army Corps of Engineers, Department of the Army, Omaha, Nebraska.

9 SUPPLEMENT FIGURES

(Page left intentionally blank)

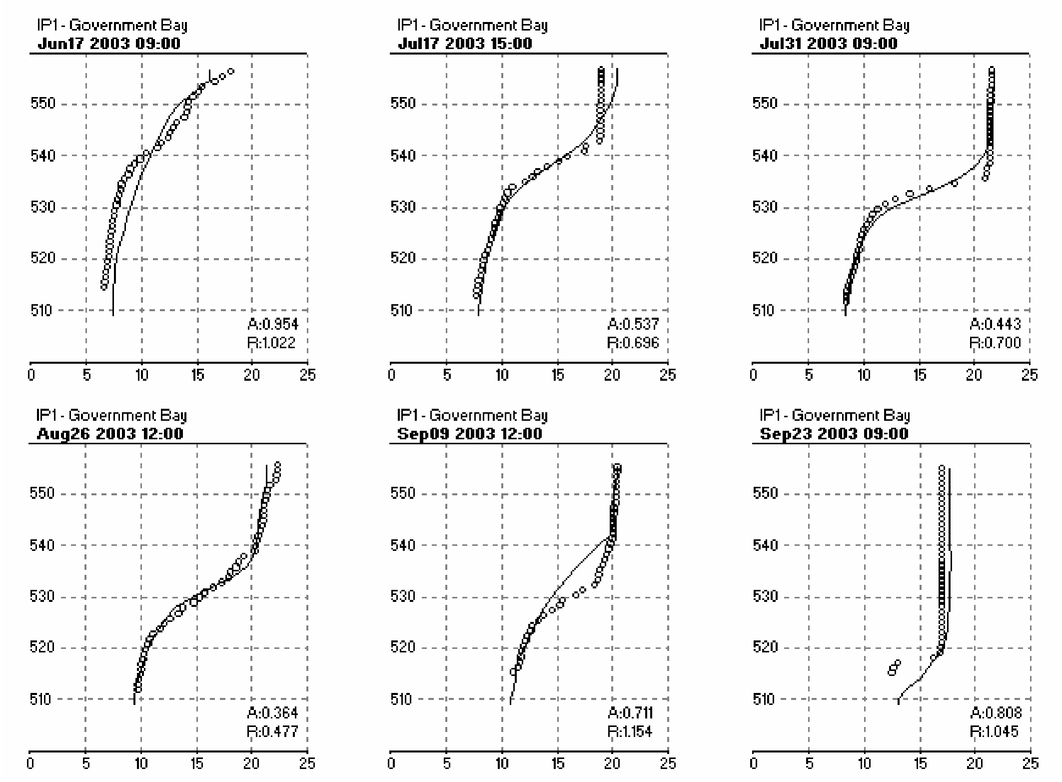


Figure 9-1. 2003 temperature calibration at IP1 – Government Bay.

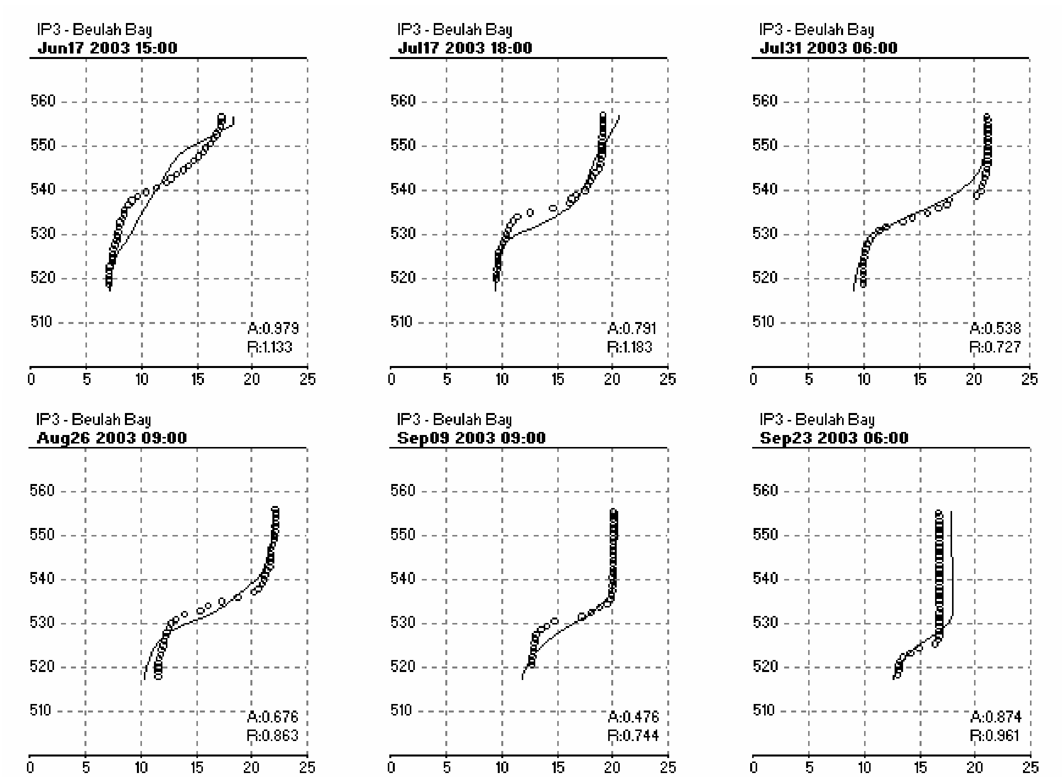


Figure 9-2. 2003 temperature calibration at IP3 – Beulah Bay.

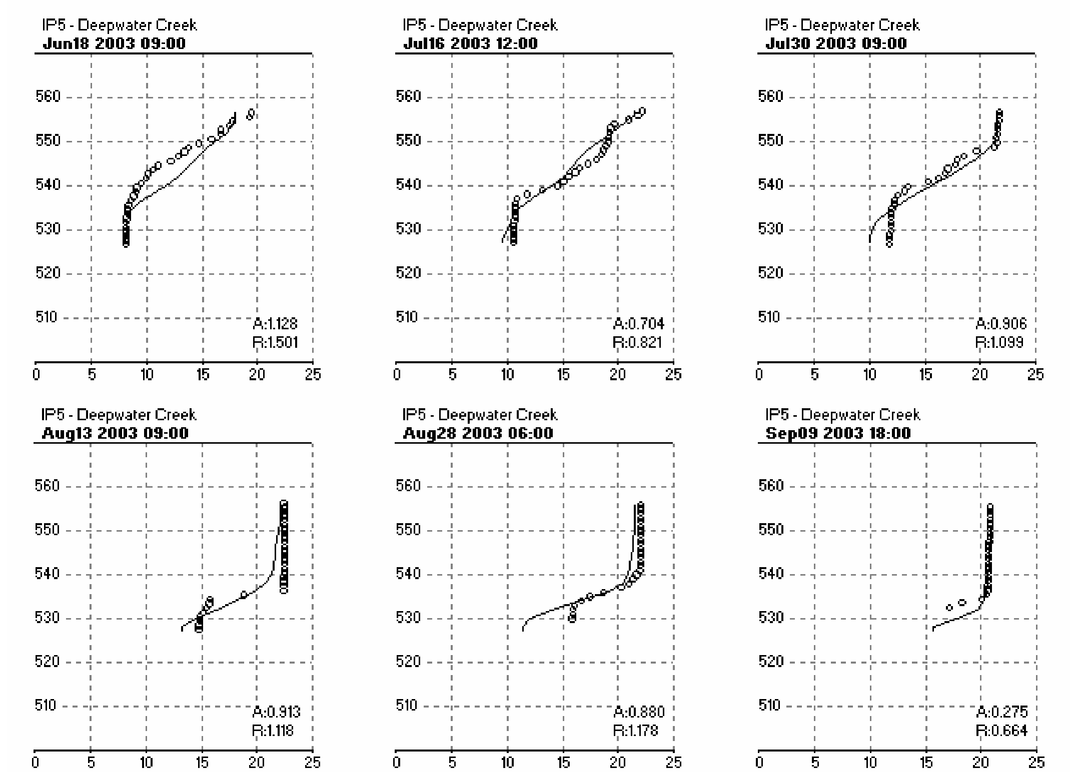


Figure 9-3. 2003 temperature calibration at IP5 – Deepwater Creek.

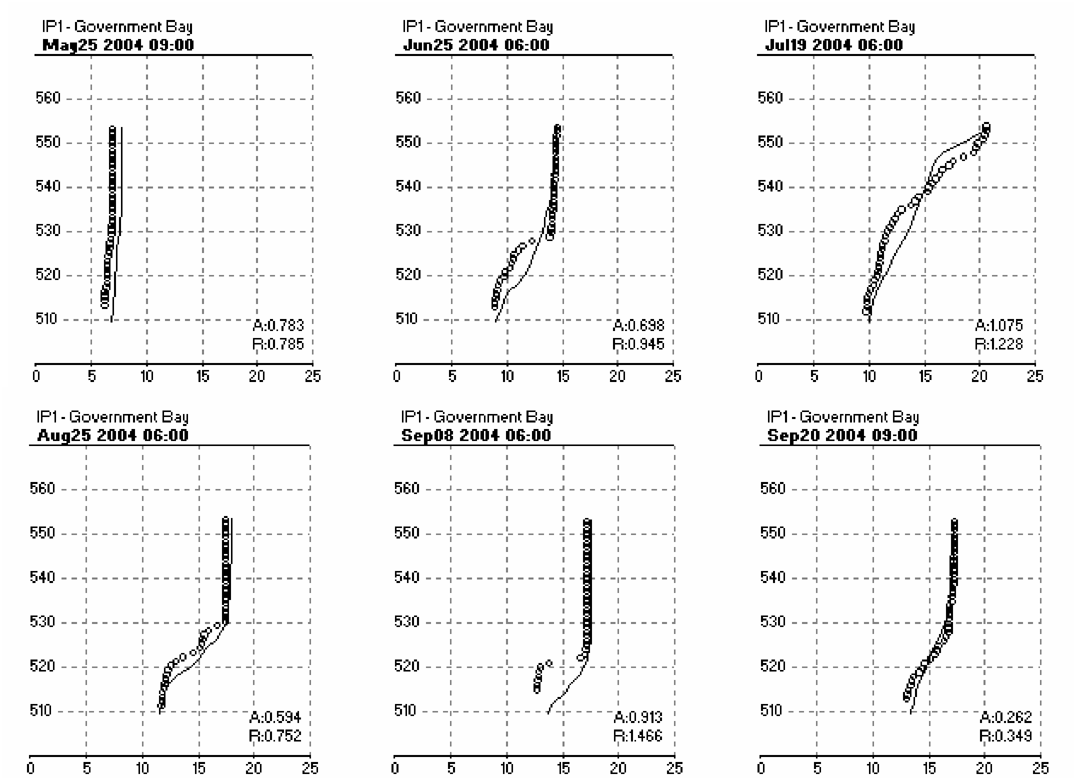


Figure 9-4. 2004 temperature calibration at IP1 – Government Bay.

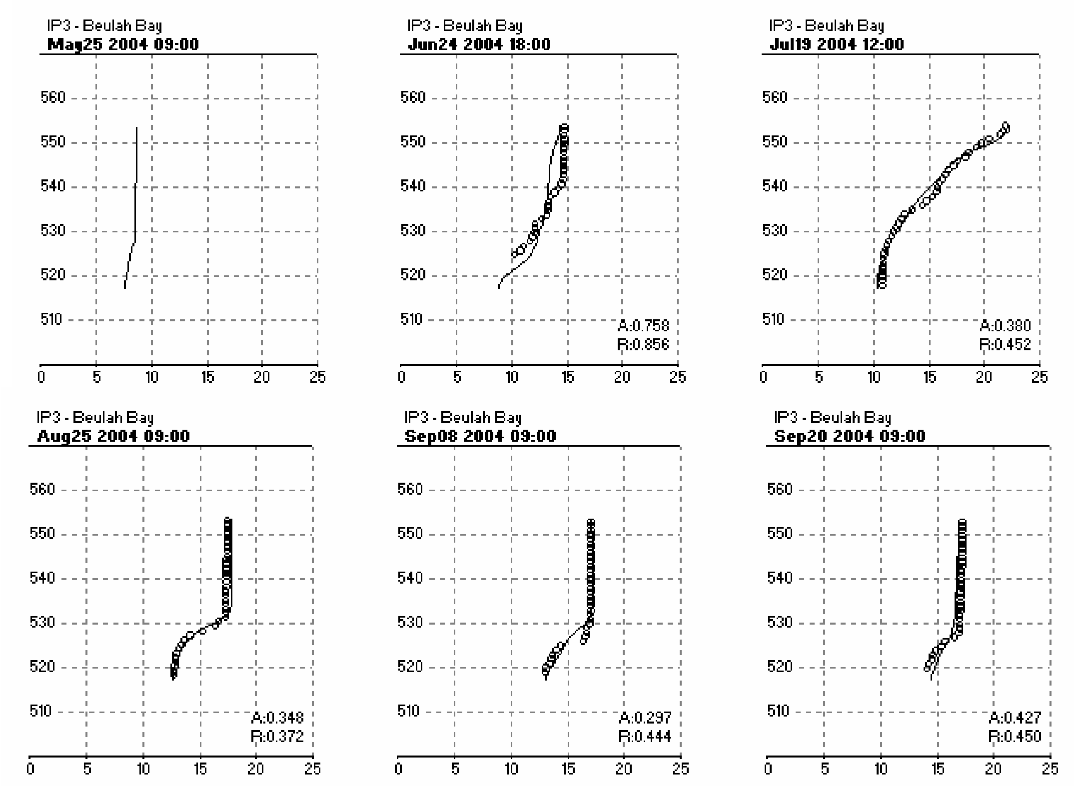


Figure 9-5. 2004 temperature calibration at IP3 – Beulah Bay.

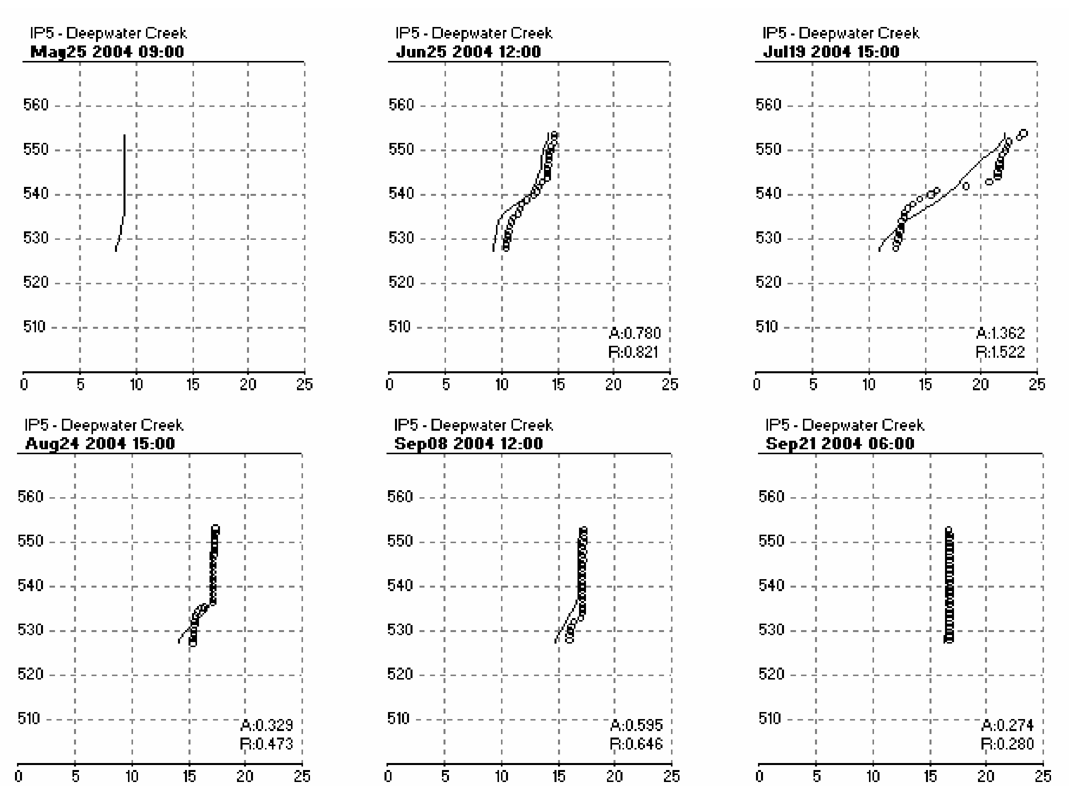


Figure 9-6. 2004 temperature calibration at IP5 – Deepwater Creek.

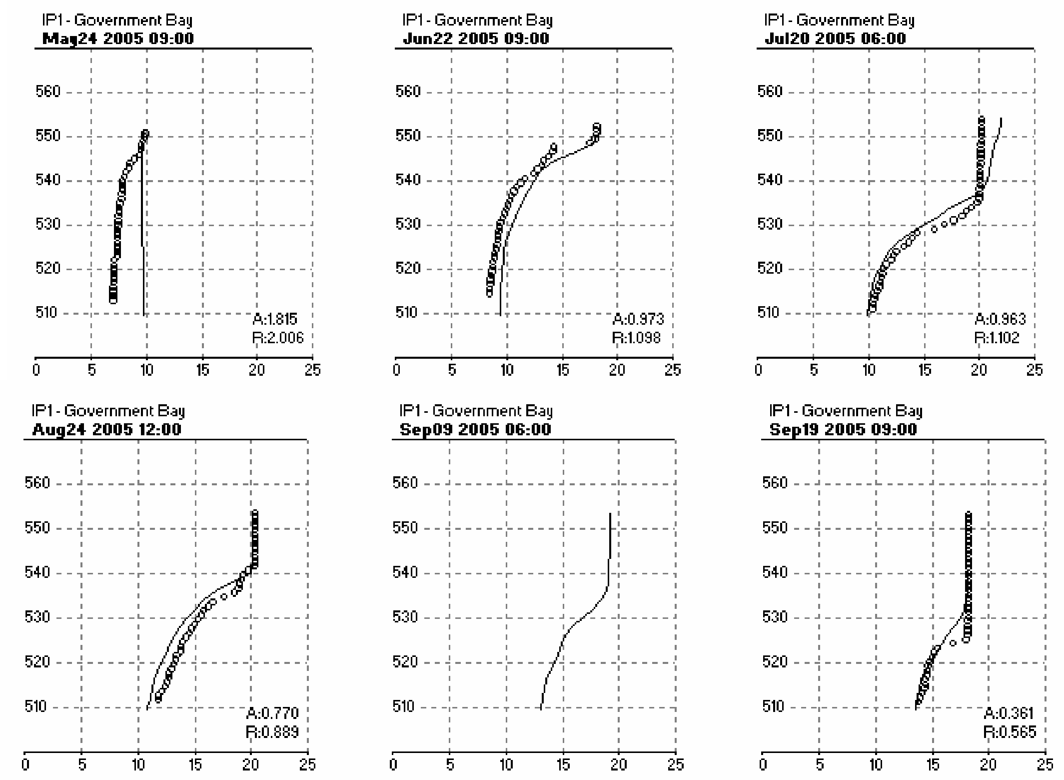


Figure 9-7. 2005 temperature calibration at IP1 – Government Bay.

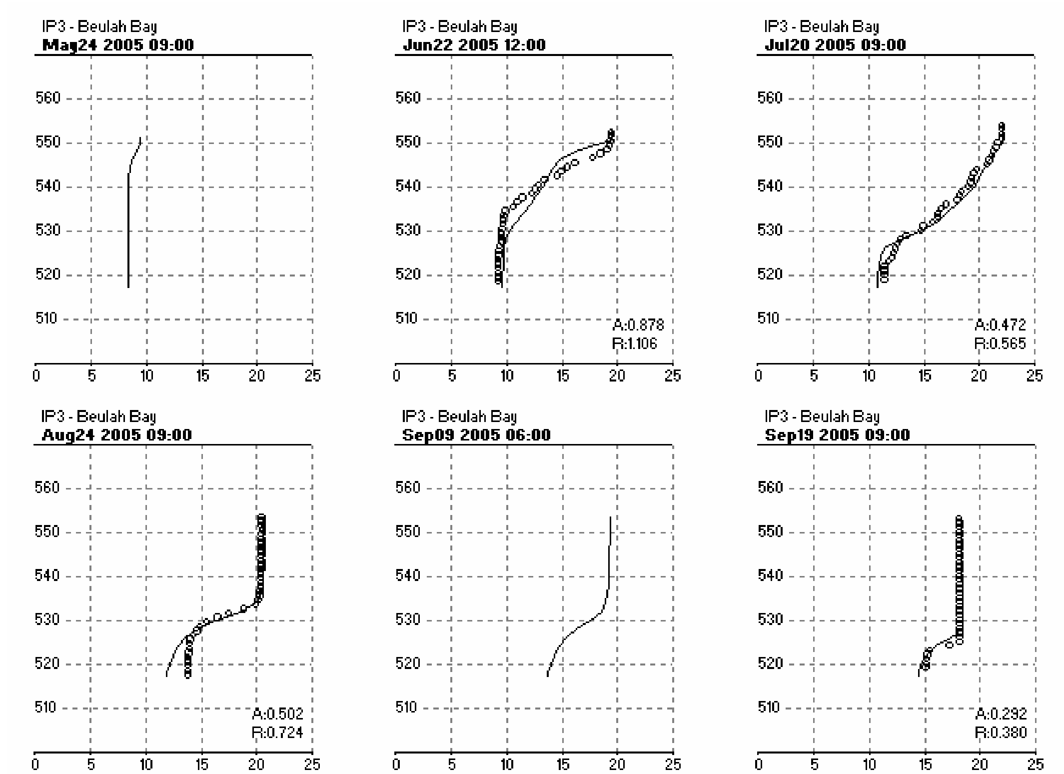


Figure 9-8. 2005 temperature calibration at IP3 – Beulah Bay.

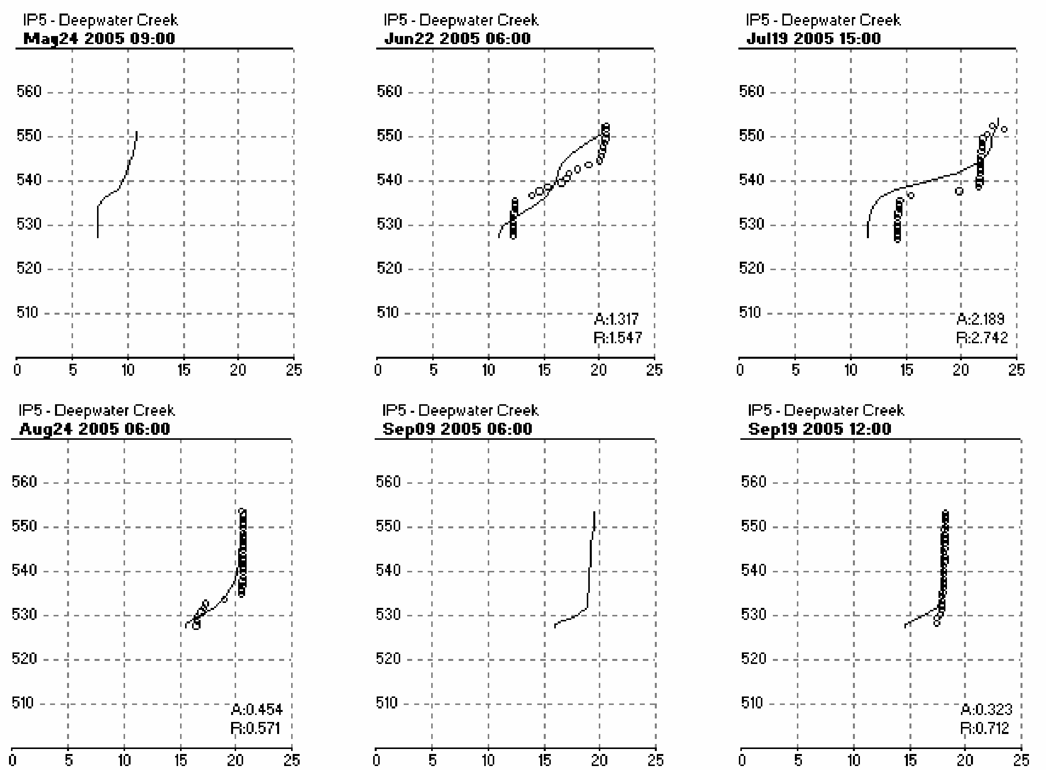


Figure 9-9. 2005 temperature calibration at IP5 – Deepwater Creek.

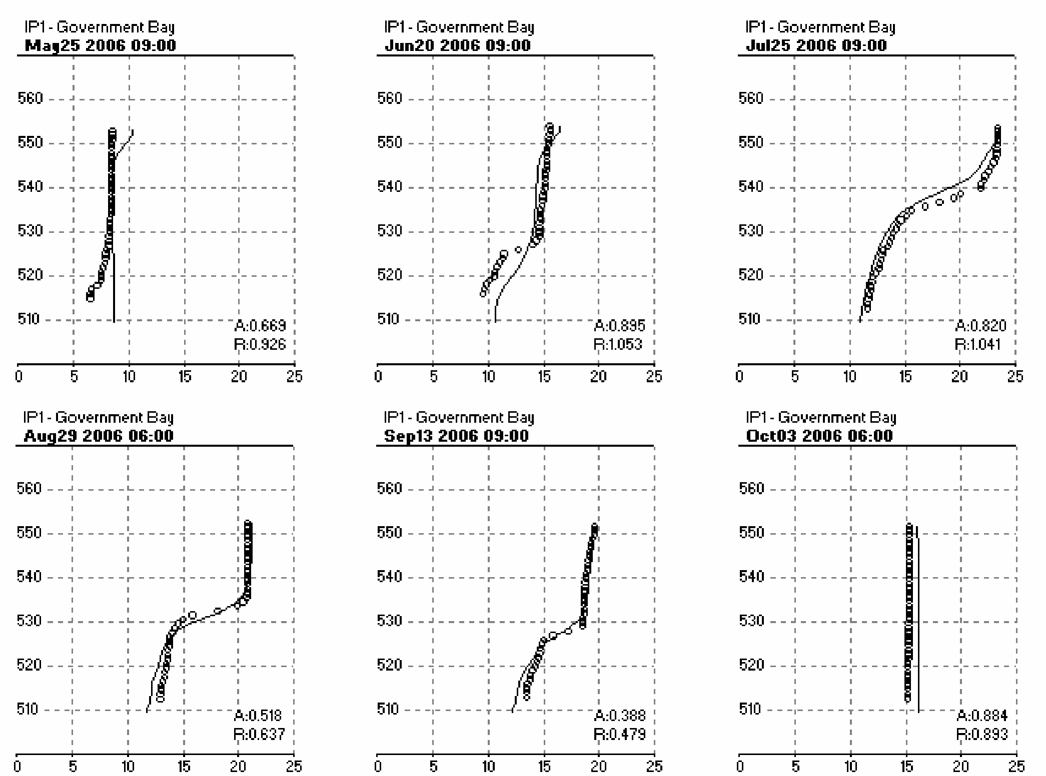


Figure 9-10. 2006 temperature calibration at IP1 – Government Bay.

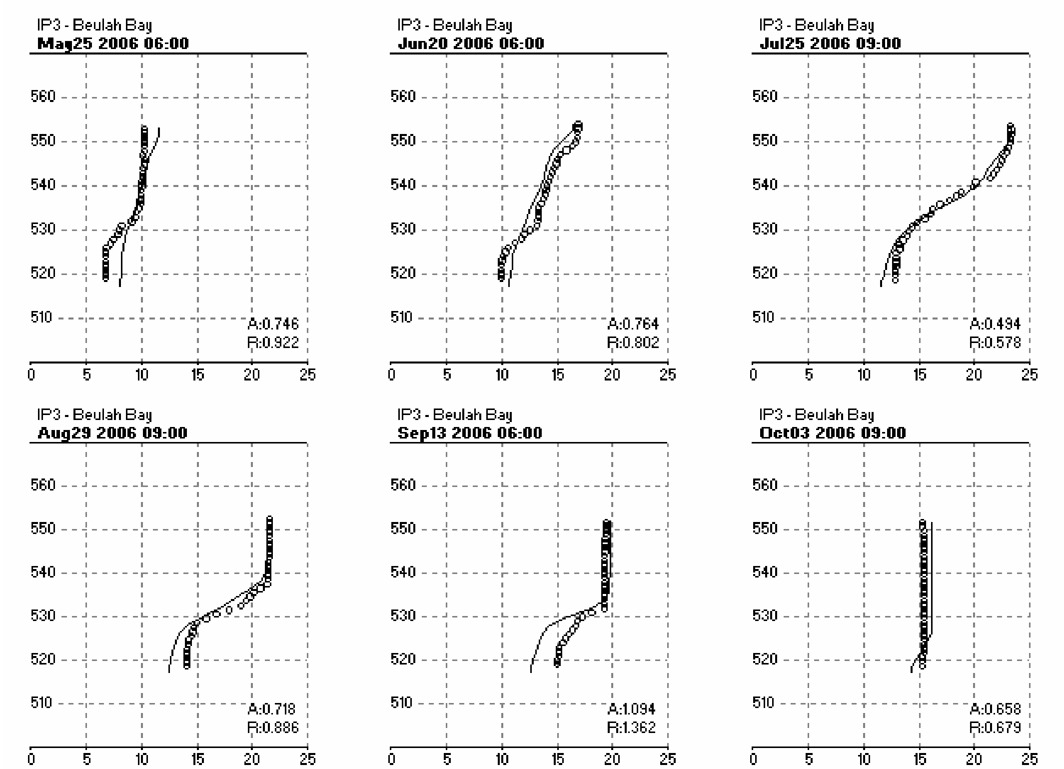


Figure 9-11. 2006 temperature calibration at IP3 – Beulah Bay.

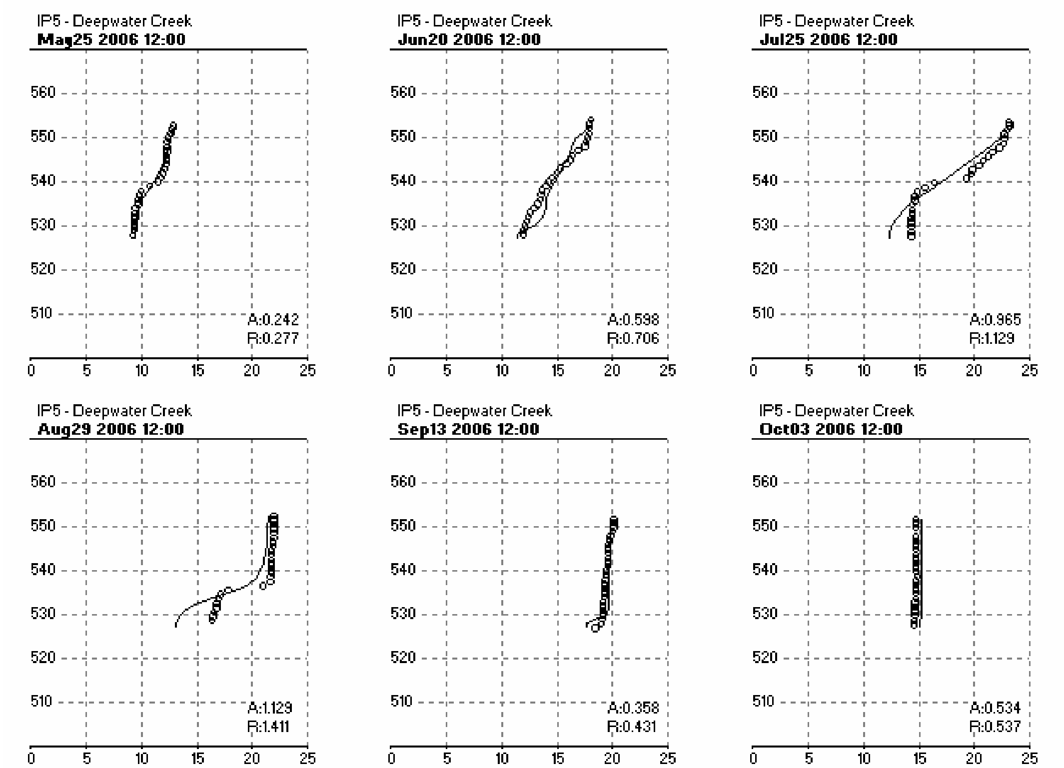


Figure 9-12. 2006 temperature calibration at IP5 – Deepwater Creek.

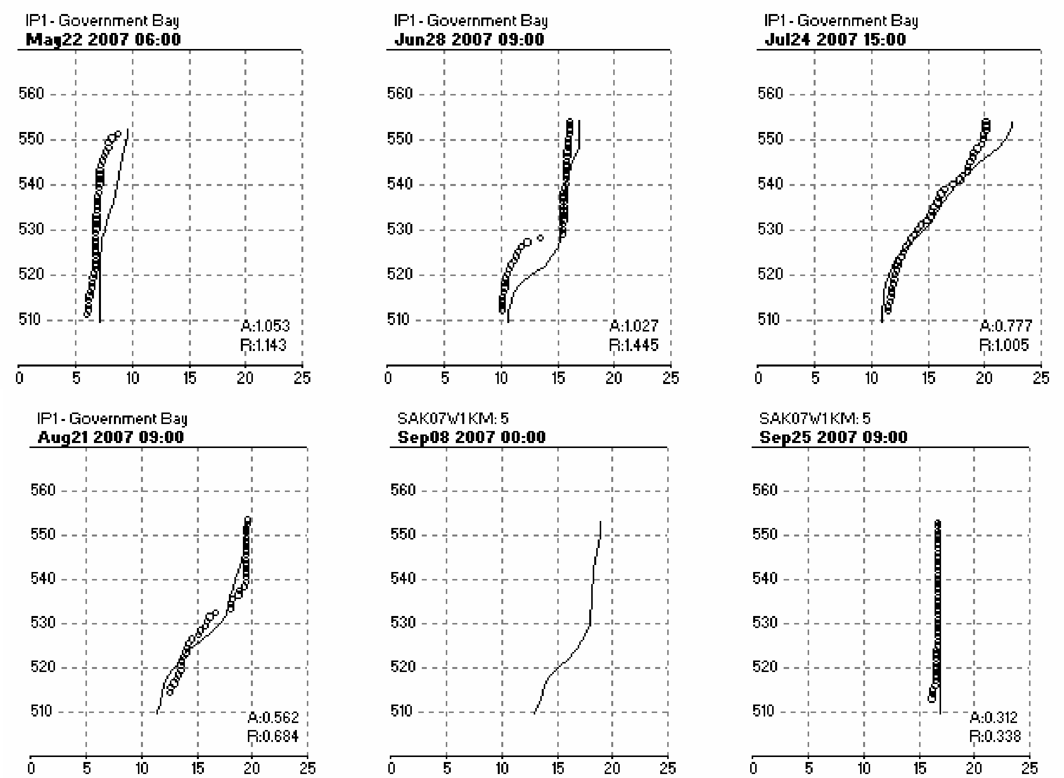


Figure 9-13. 2007 temperature calibration at IP1 – Government Bay.

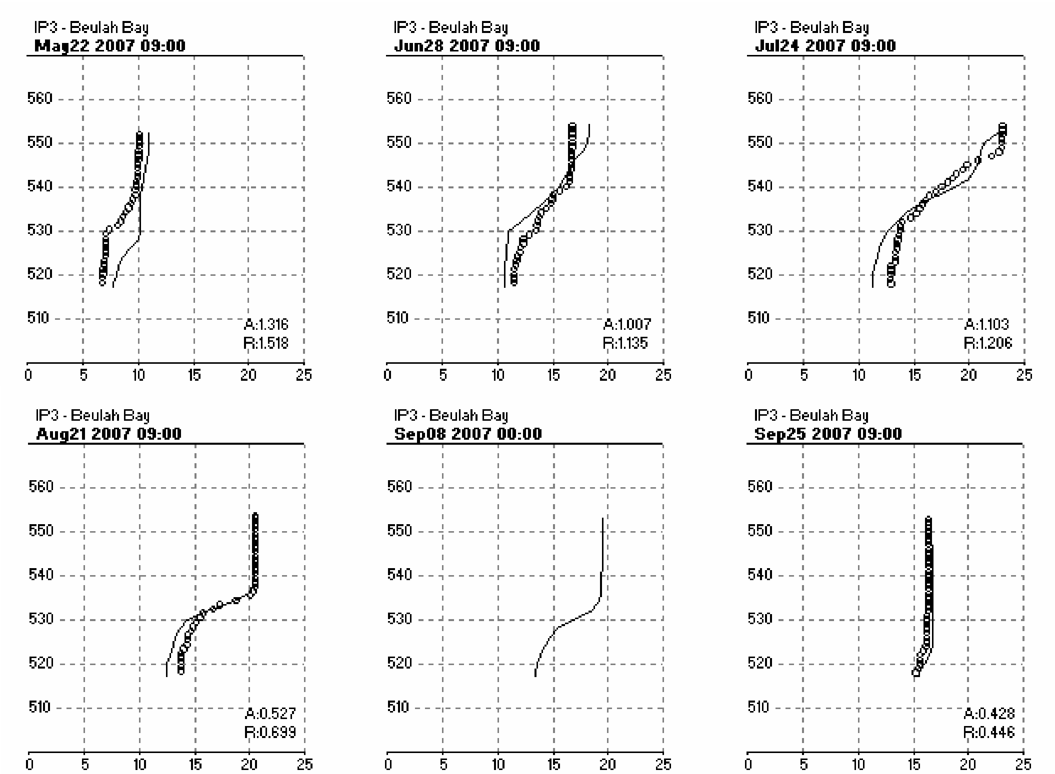


Figure 9-14. 2007 temperature calibration at IP3 – Beulah Bay.

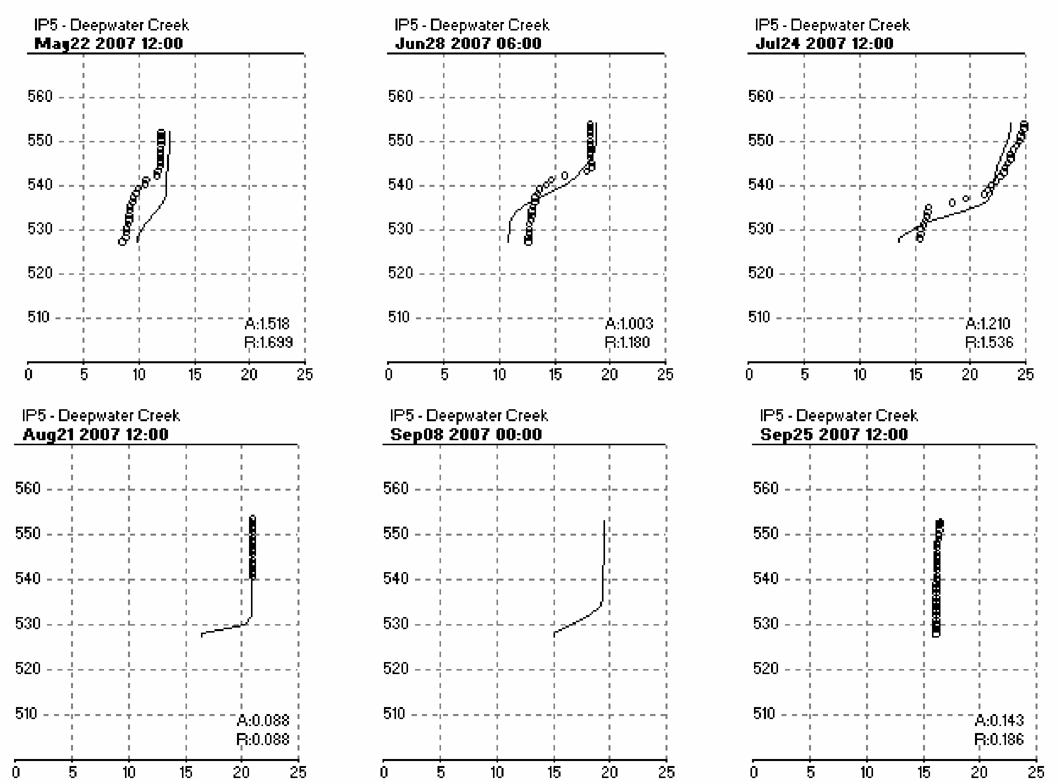


Figure 9-15. 2007 temperature calibration at IP5 – Deepwater Creek.

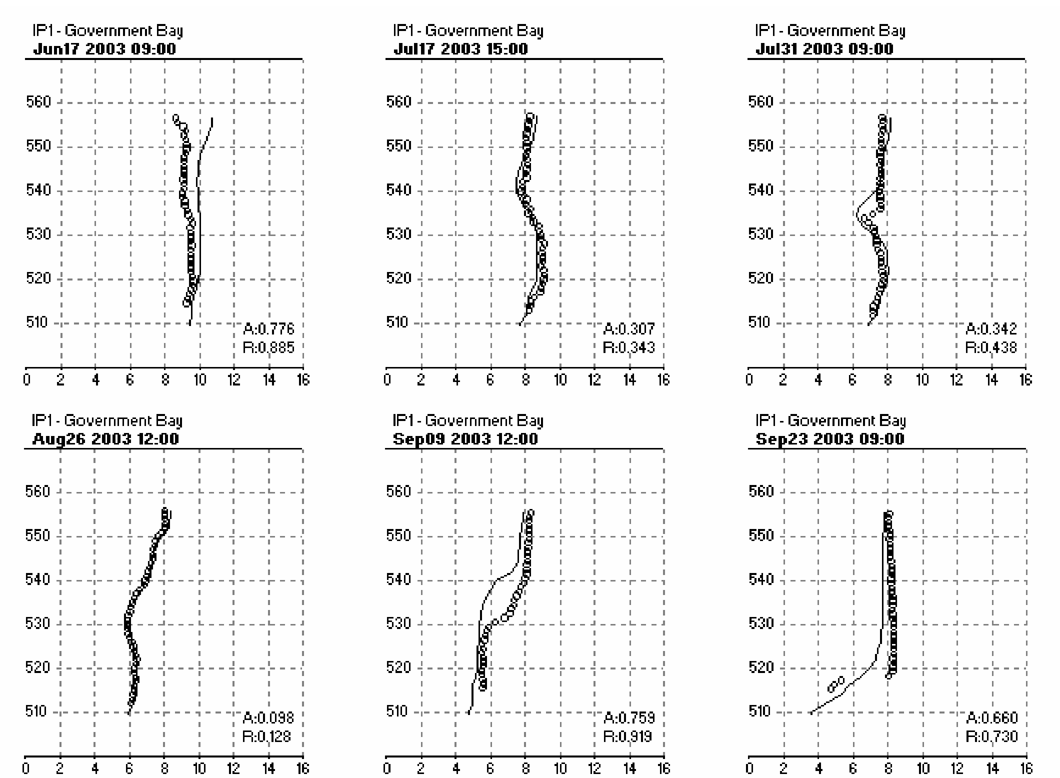


Figure 9-16. 2003 dissolved oxygen calibration at IP1 – Government Bay.

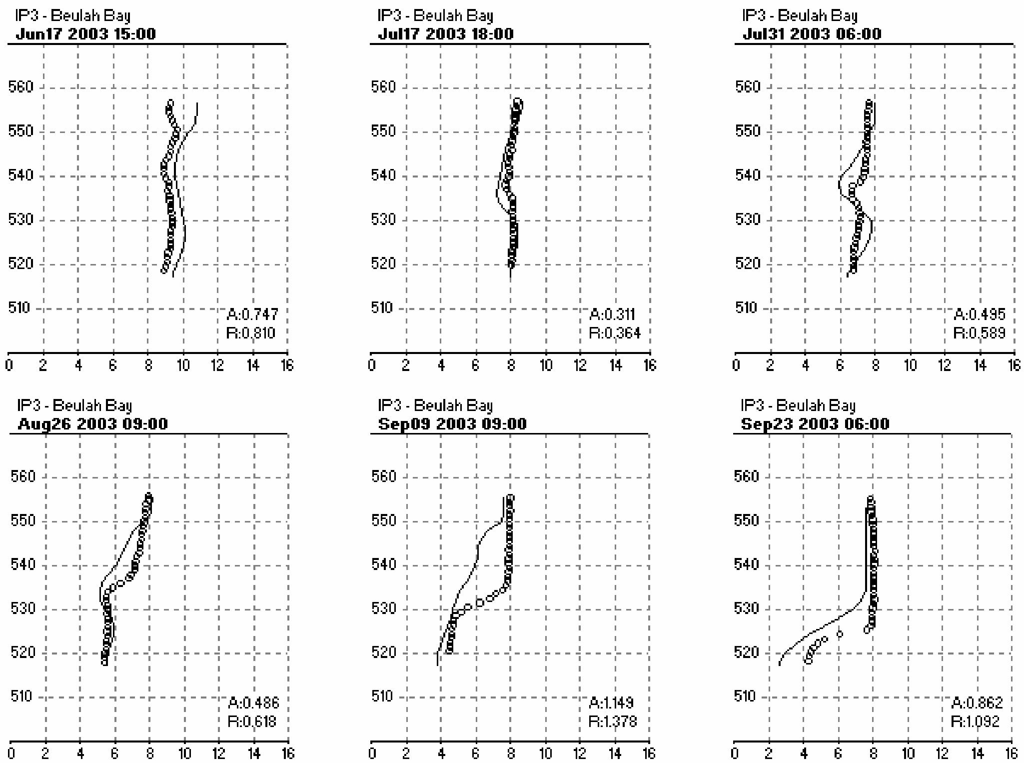


Figure 9-17. 2003 dissolved oxygen calibration at IP3 – Beulah Bay.

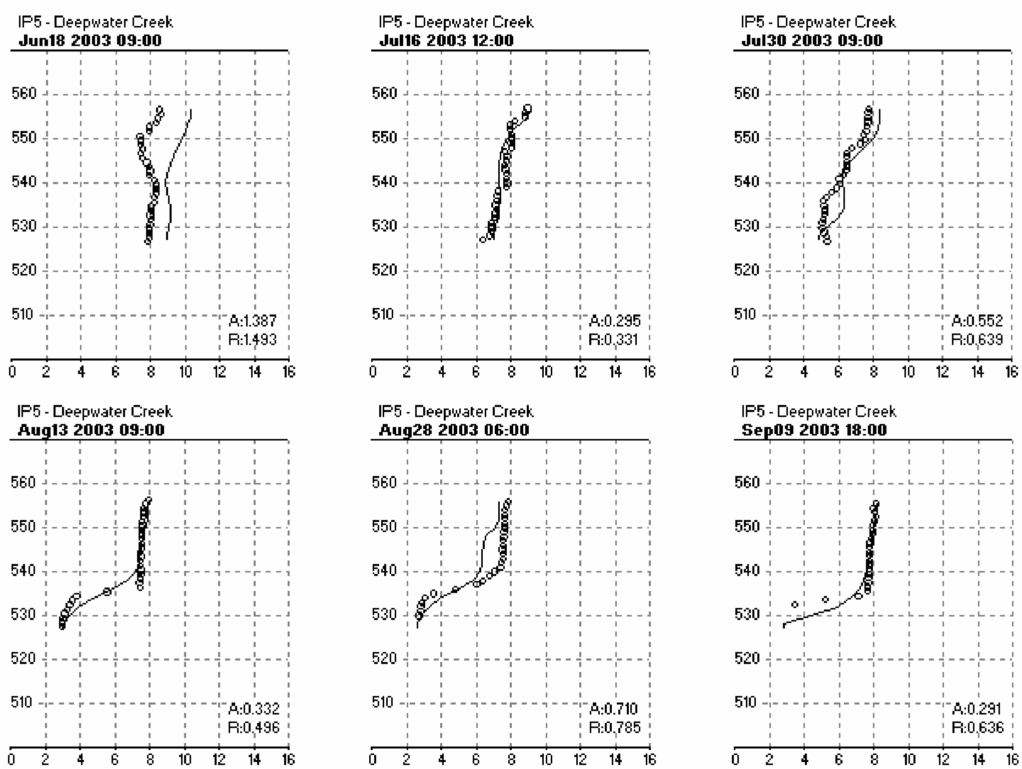


Figure 9-18. 2003 dissolved oxygen calibration at IP5 – Deepwater Creek.

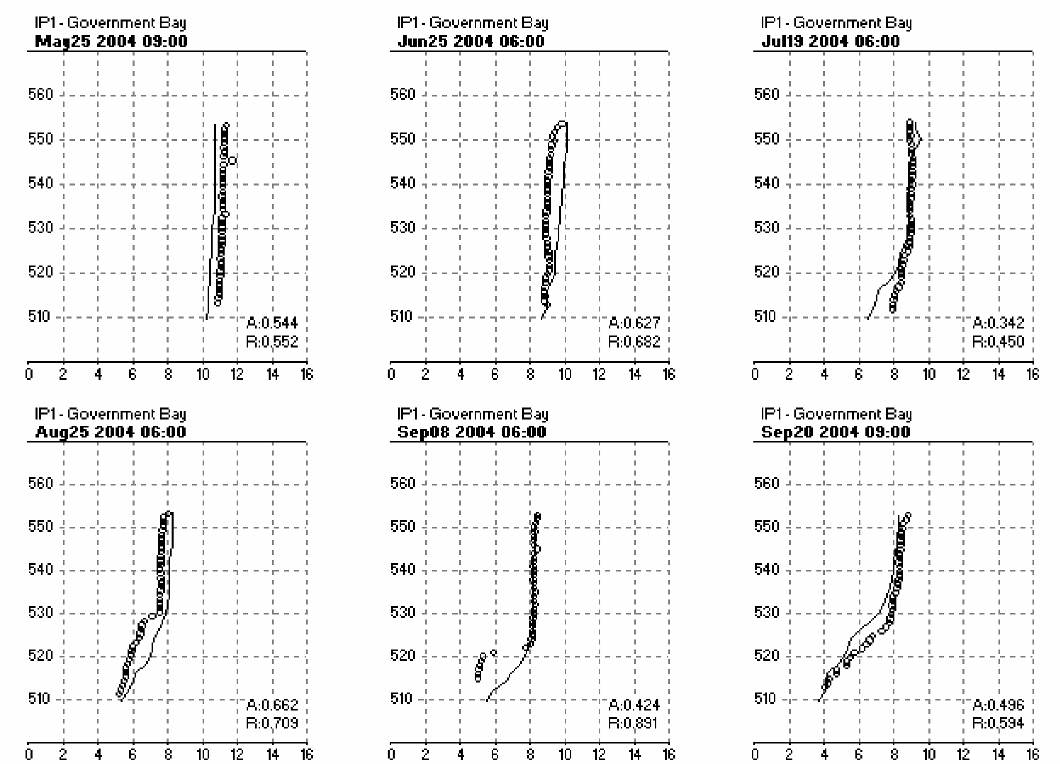


Figure 9-19. 2004 dissolved oxygen calibration at IP1 – Government Bay.

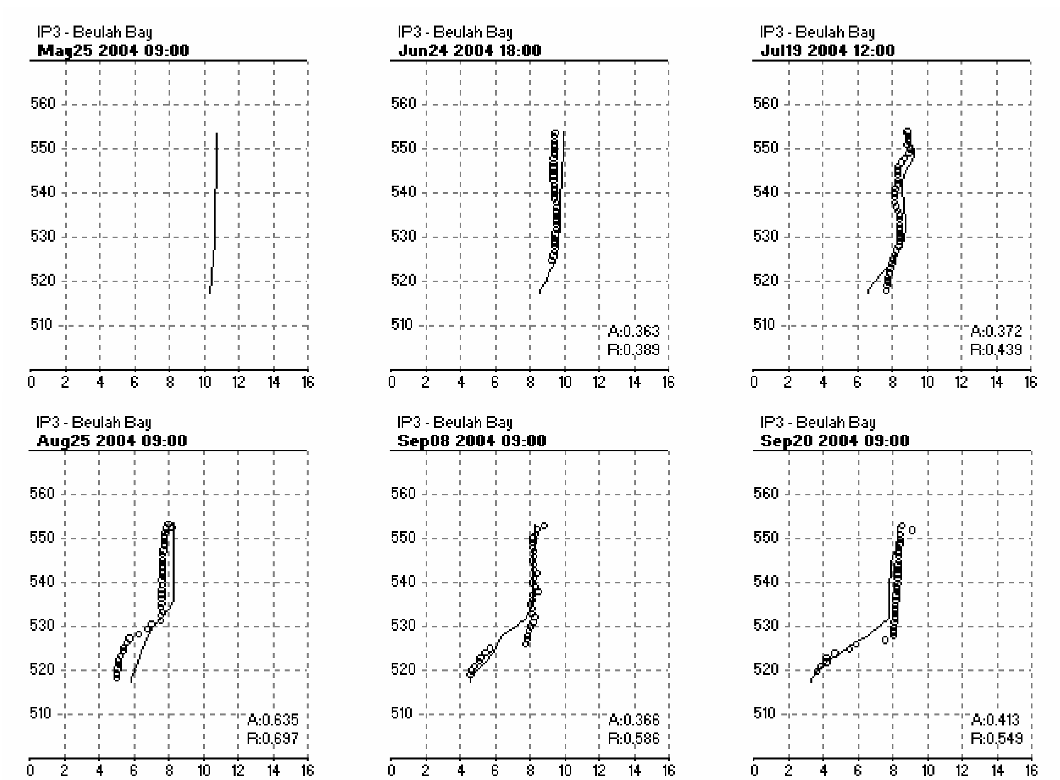


Figure 9-20. 2004 dissolved oxygen calibration at IP3 – Beulah Bay.

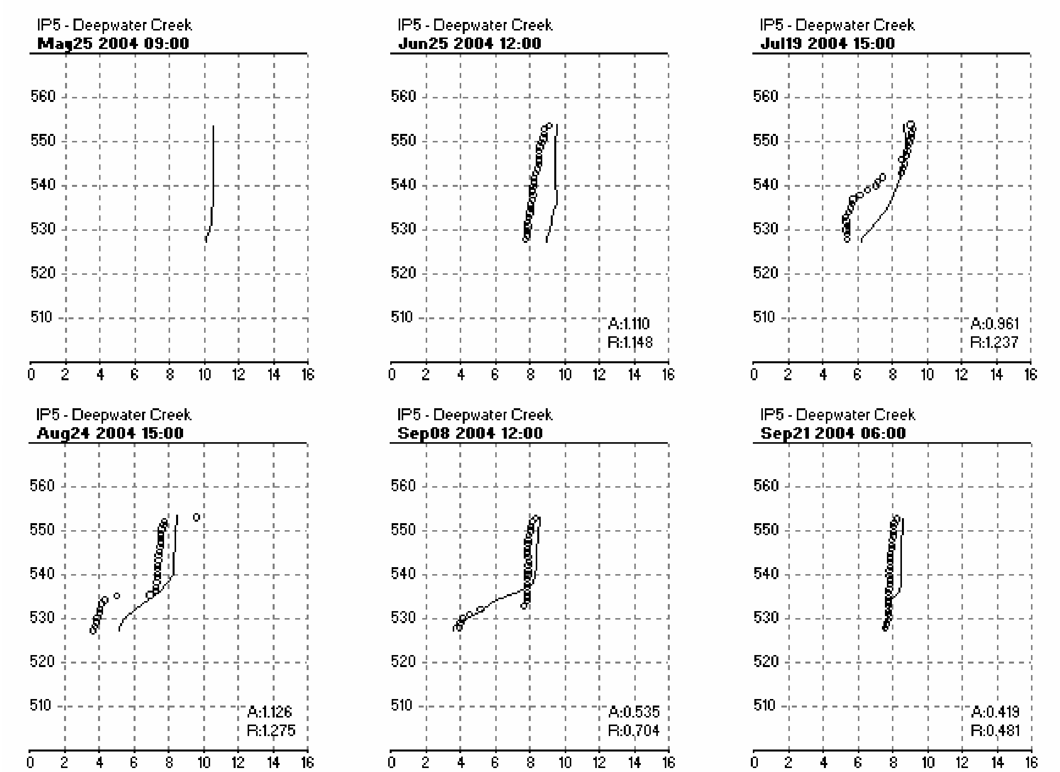


Figure 9-21. 2004 dissolved oxygen calibration at IP5 – Deepwater Creek.

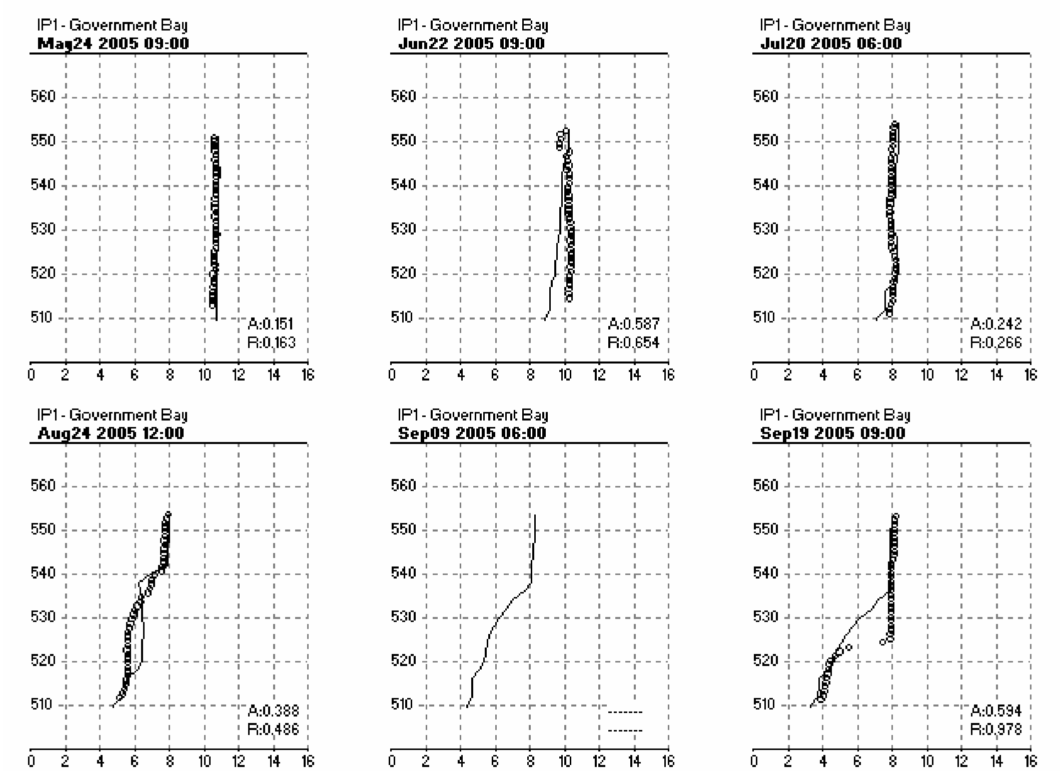


Figure 9-22. 2005 dissolved oxygen calibration at IP1 – Government Bay.

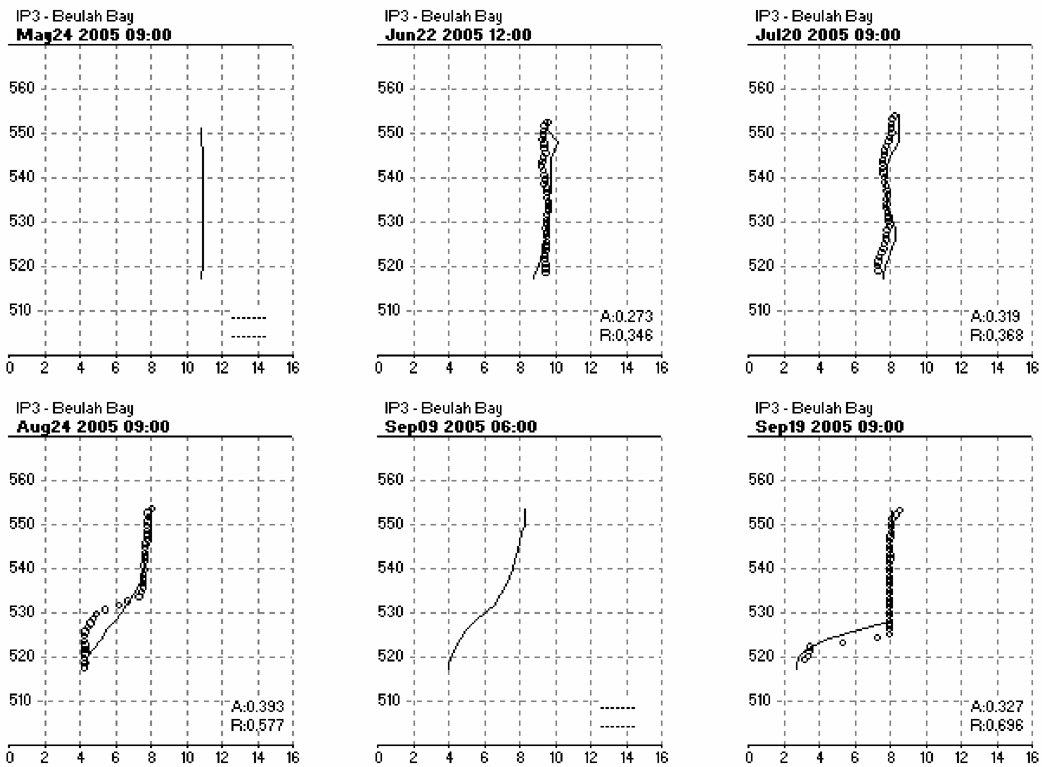


Figure 9-23. 2005 dissolved oxygen calibration at IP3 – Beulah Bay.

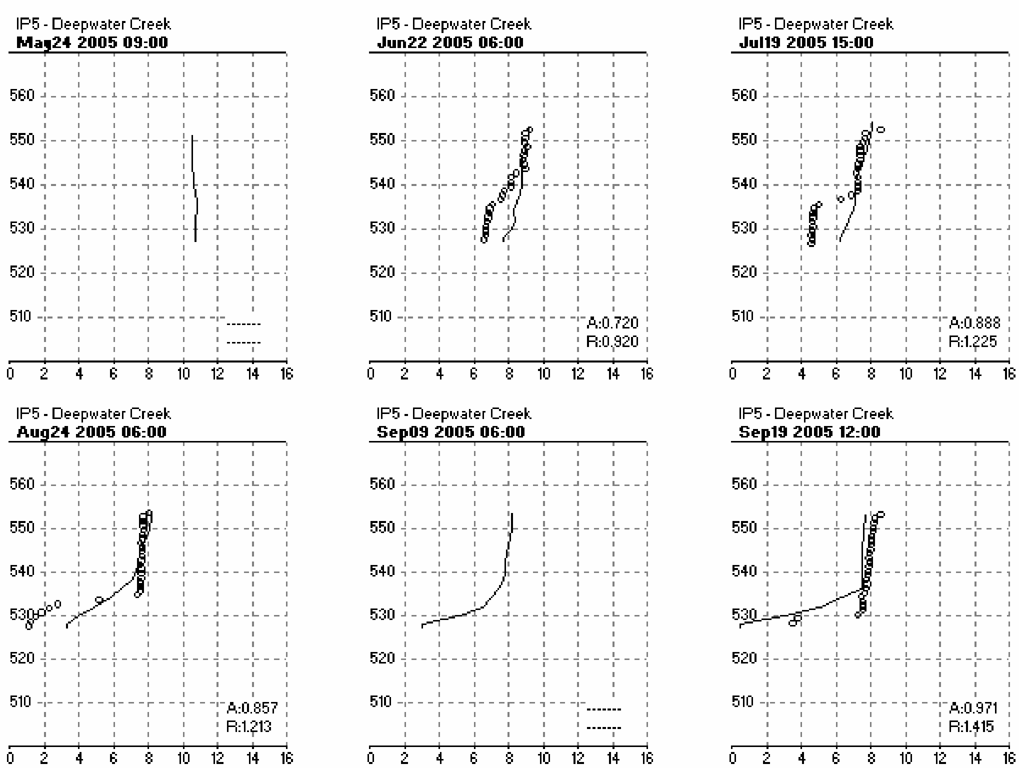


Figure 9-24. 2005 dissolved oxygen calibration at IP5 – Deepwater Creek.

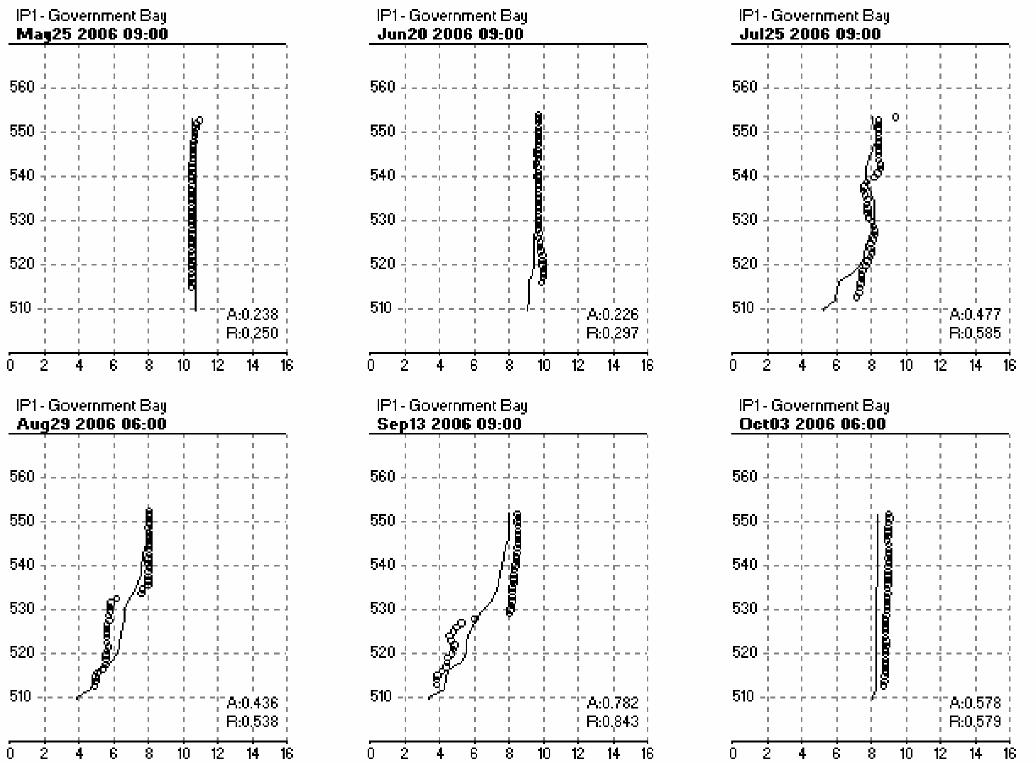


Figure 9-25. 2006 dissolved oxygen calibration at IP1 – Government Bay.

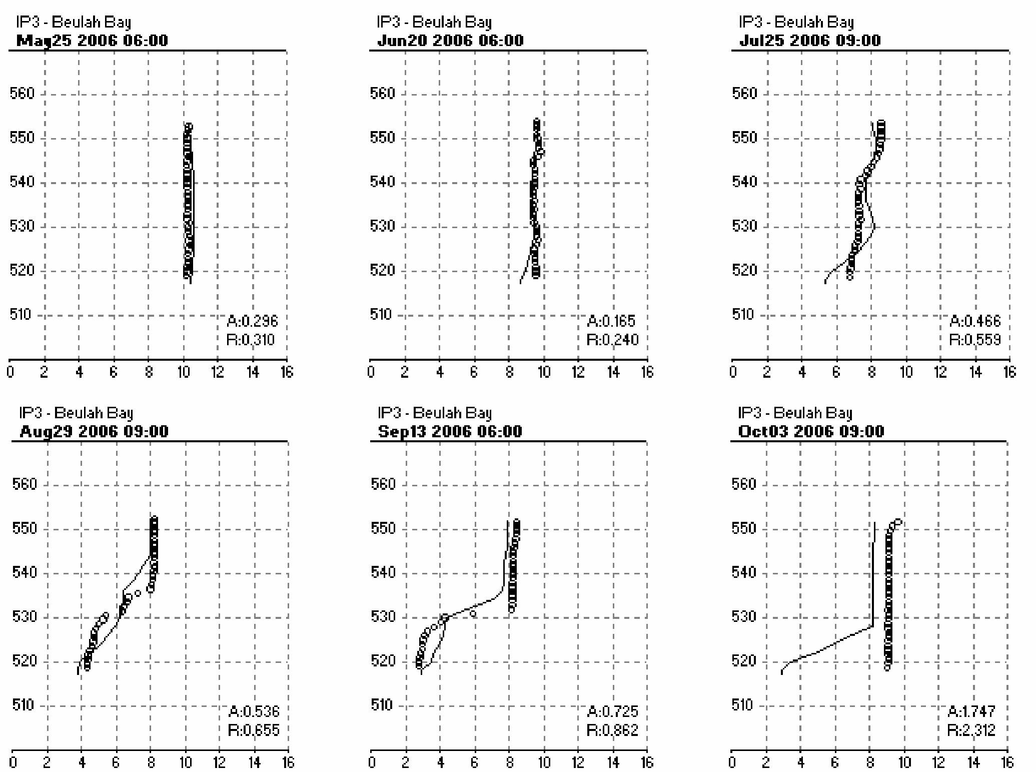


Figure 9-26. 2006 dissolved oxygen calibration at IP3 – Beulah Bay.

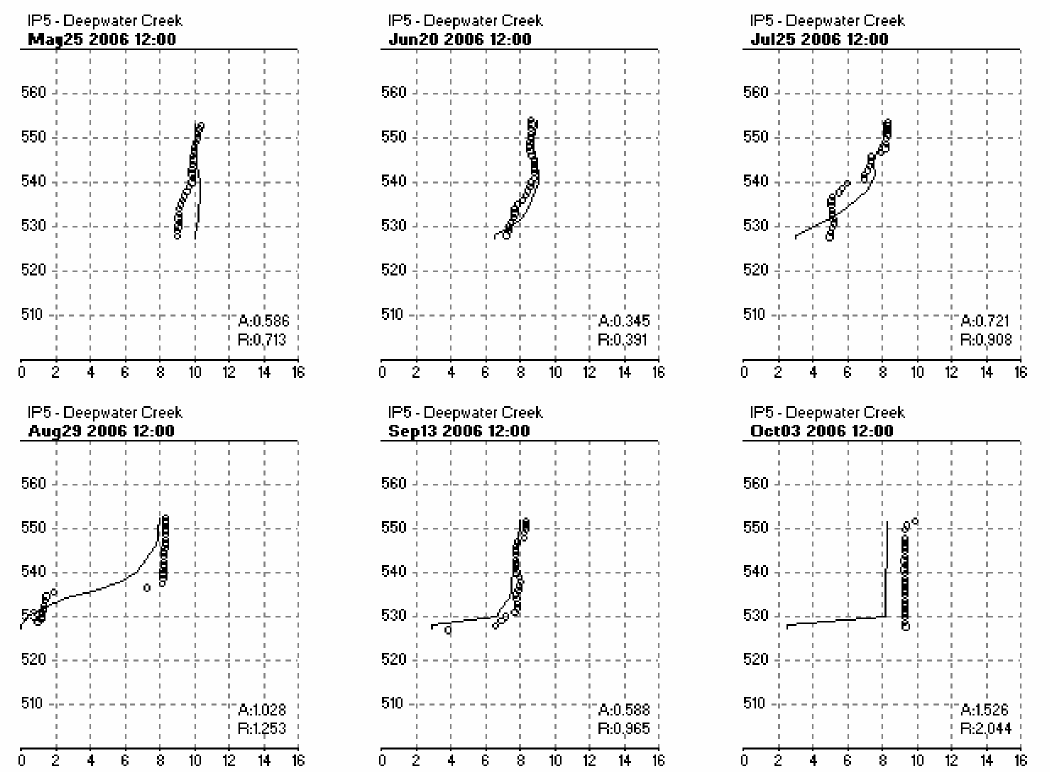


Figure 9-27. 2006 dissolved oxygen calibration at IP5 – Deepwater Creek.

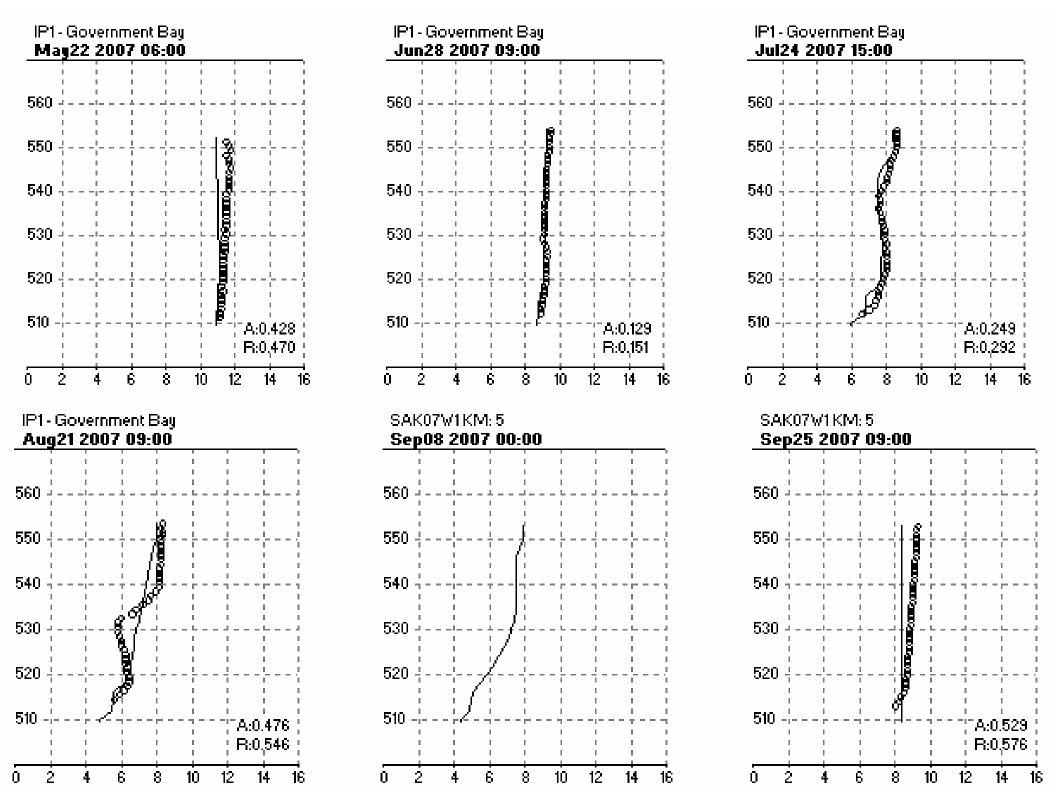


Figure 9-28. 2007 dissolved oxygen calibration at IP1 – Government Bay.

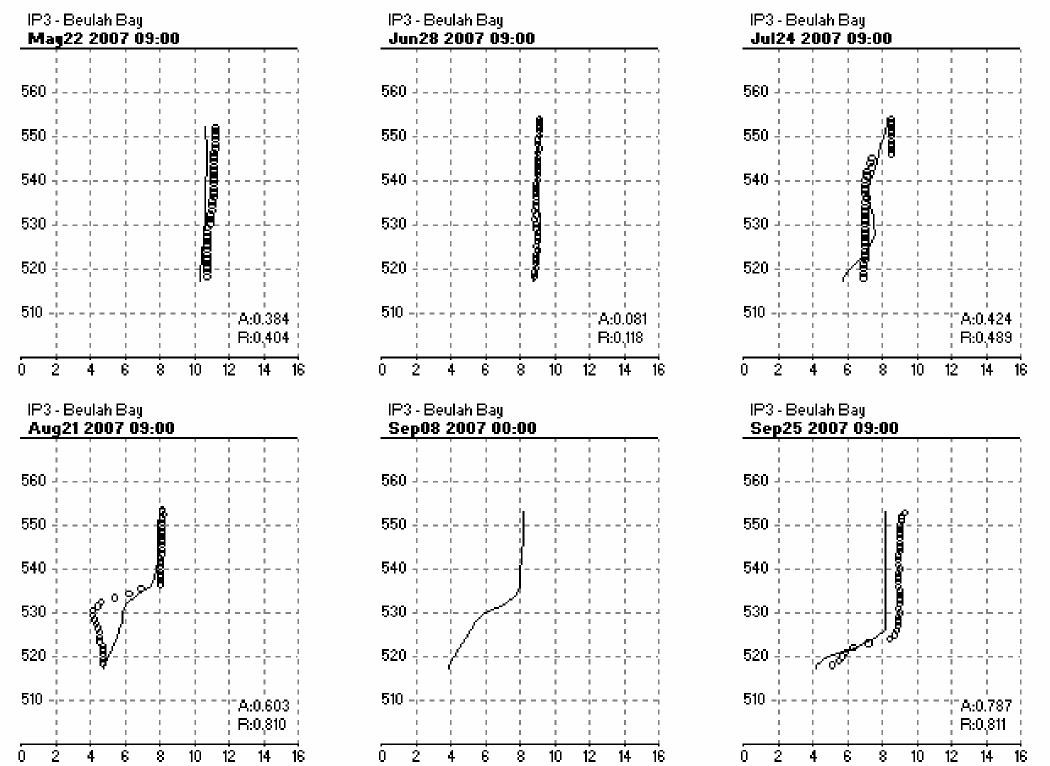


Figure 9-29. 2007 dissolved oxygen calibration at IP3 – Beulah Bay.

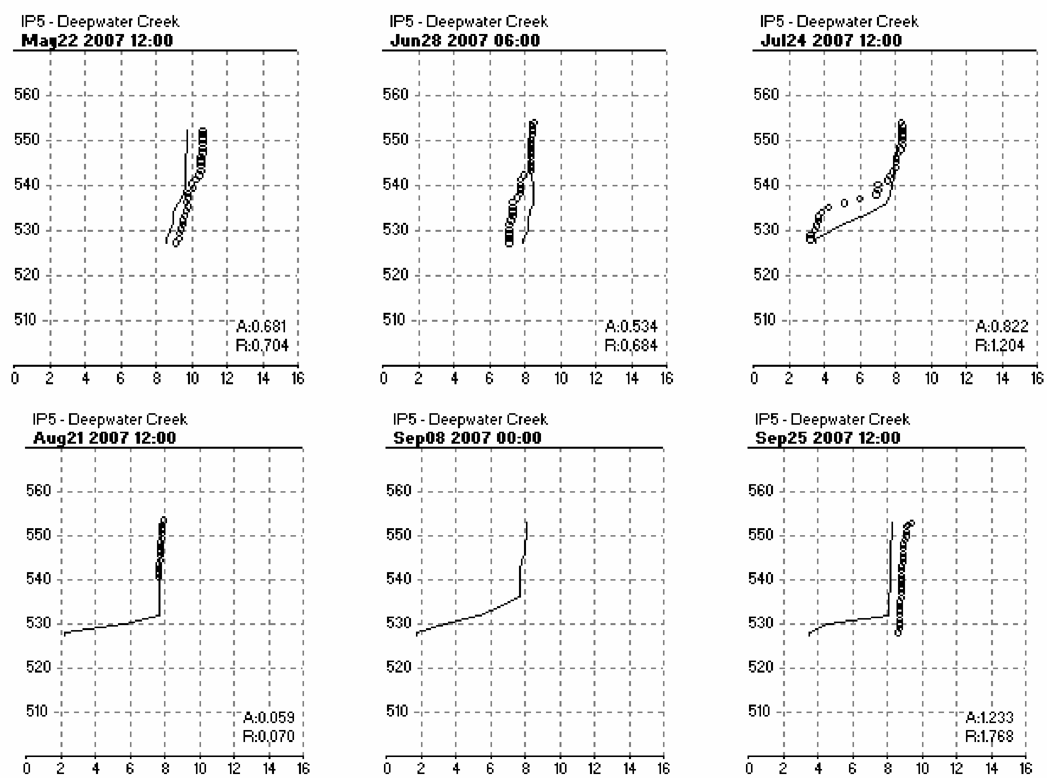


Figure 9-30. 2007 dissolved oxygen calibration at IP5 – Deepwater Creek.